Fundamental Symmetries and Neutrinos

from 30,000 feet

RHIC & AGS Annual Users' Meeting, June 26, 2013

with thanks to David Hertzog, who provided most of the Fundamental Symmetries slides

Hamish Robertson, CENPA, University of Washington

Ray Davis and John Bahcall with the first solar neutrino detector

Goldhaber-Grodzins-Sunyar experiment (Lee Grodzins 1958)

Precision Physics Motivation II: Burning issues

- The Standard Model as we know it has been built on an enormous experimental foundation involving ***Precision*** and ***Energy*** frontier efforts
- And, some exquisite ***Theory*** !
- **Are the Standard Model predictions complete and correct? (no)**
- **The community has also begun to worry …**

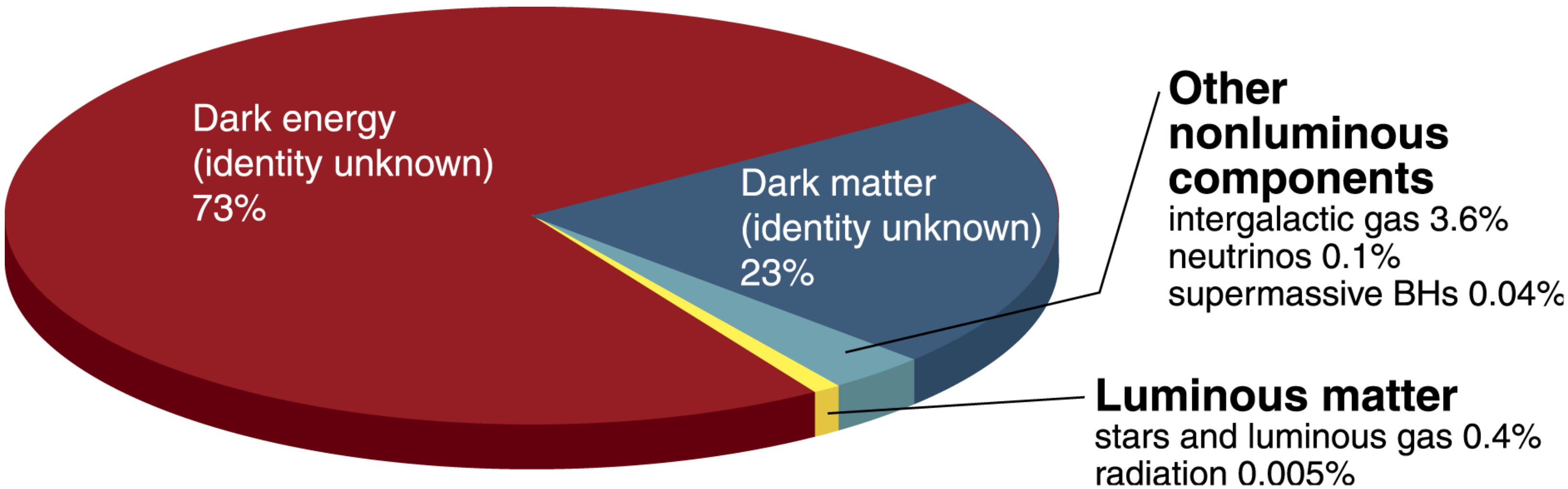
So far: No direct evidence for Supersymmetry, Extra Dimensions, 4th Generation, New Dynamics…

At The LHC!

The Higgs – Last Particle Ever Discovered?

Marciano

The Universe -- A very odd place



And why is there **matter** but no **antimatter**?

Sakharov's criteria:

Baryon number not conserved…

CP violated…

Universe not in equilibrium at some point…

New Physics through precision and sensitivity

- Beta decay: μ, n, nuclei
  - TWIST, PERC, UCNA, ^{6}He
- Muon anomaly
  - g-2
- cLFV
  - MEG, Mu2e, COMET, Mu3e
- EDMs
  - Hg, n, storage rings, …
- PV electron scattering
  - Moller, Qweak, …
- Lepton universality
  - PEN, PIENU
- $0\nu\beta\beta$
  - EXO, Ge, Cuore, …

SM Extensions
SUSY, …

SM Extensions
Dark Matter, SUSY, Dark Photons, many others

SM Extensions
SUSY, new interactions

Baryon Asymmetry
SUSY, θ_{QCD}

SM Extensions or $\mathrm{Sin}^2\theta_W$
SUSY, Z’, Dark Photons

SM Extensions
Various SUSY limits

Baryon Asymmetry
Majorana / Dirac neutrinos

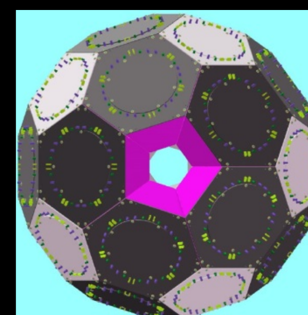
+ many Direct Dark Matter searches, Dark Photon searches, Axion searches, …

Resolved Conflicts:

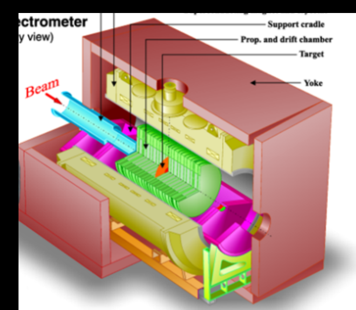
Lesson: The Standard Model is hard to crack

g_a, g_v, V_{ud} & “Row 1 unitarity”

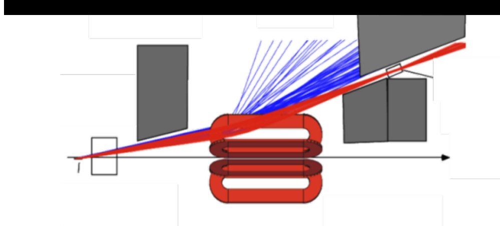
G_F, τ_μ, g_P



$\mathrm{Sin}^2\theta_W$



Michel parameters

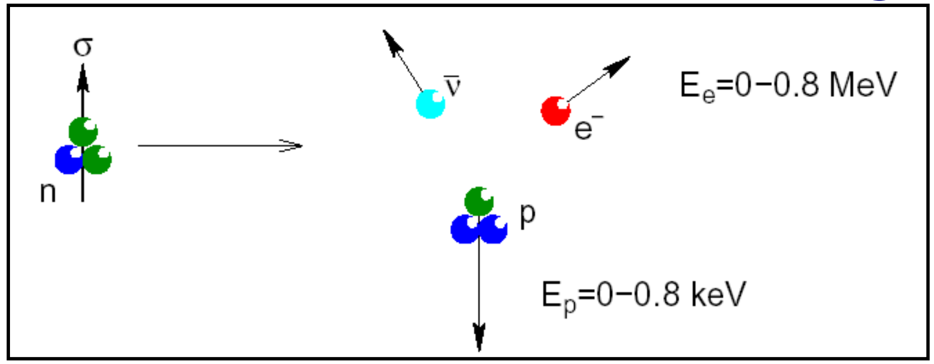


The Neutron as a Fundamental Laboratory

$n \rightarrow p^+ + e^- + \nu'_e$

neutron lifetime $\tau \approx 15$ min

β-endpoint energy: $E_{max} = 782$ keV



$$dW \propto \frac{1}{\tau_n} F(E_e)\left[1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\upsilon}{E_e \cdot E_\upsilon} + b\frac{m_e}{E_e} + A\frac{\sigma_n \cdot \mathbf{p}_e}{E_e} + B\frac{\sigma_n \cdot \mathbf{p}_\upsilon}{E_\upsilon}\right]$$

$$\boxed{\tau_n \propto 1/(g_A^2 + 3g_V^2)}$$

$$\boxed{a = \frac{1 - \left(\frac{g_A}{g_V}\right)^2}{1 - 3\left(\frac{g_A}{g_V}\right)}}$$

$$\boxed{b = 0}$$

$$\boxed{A = -2\frac{\left(\frac{g_A}{g_V}\right)^2 + \left(\frac{g_A}{g_V}\right)}{1 - 3\left(\frac{g_A}{g_V}\right)^2}}$$

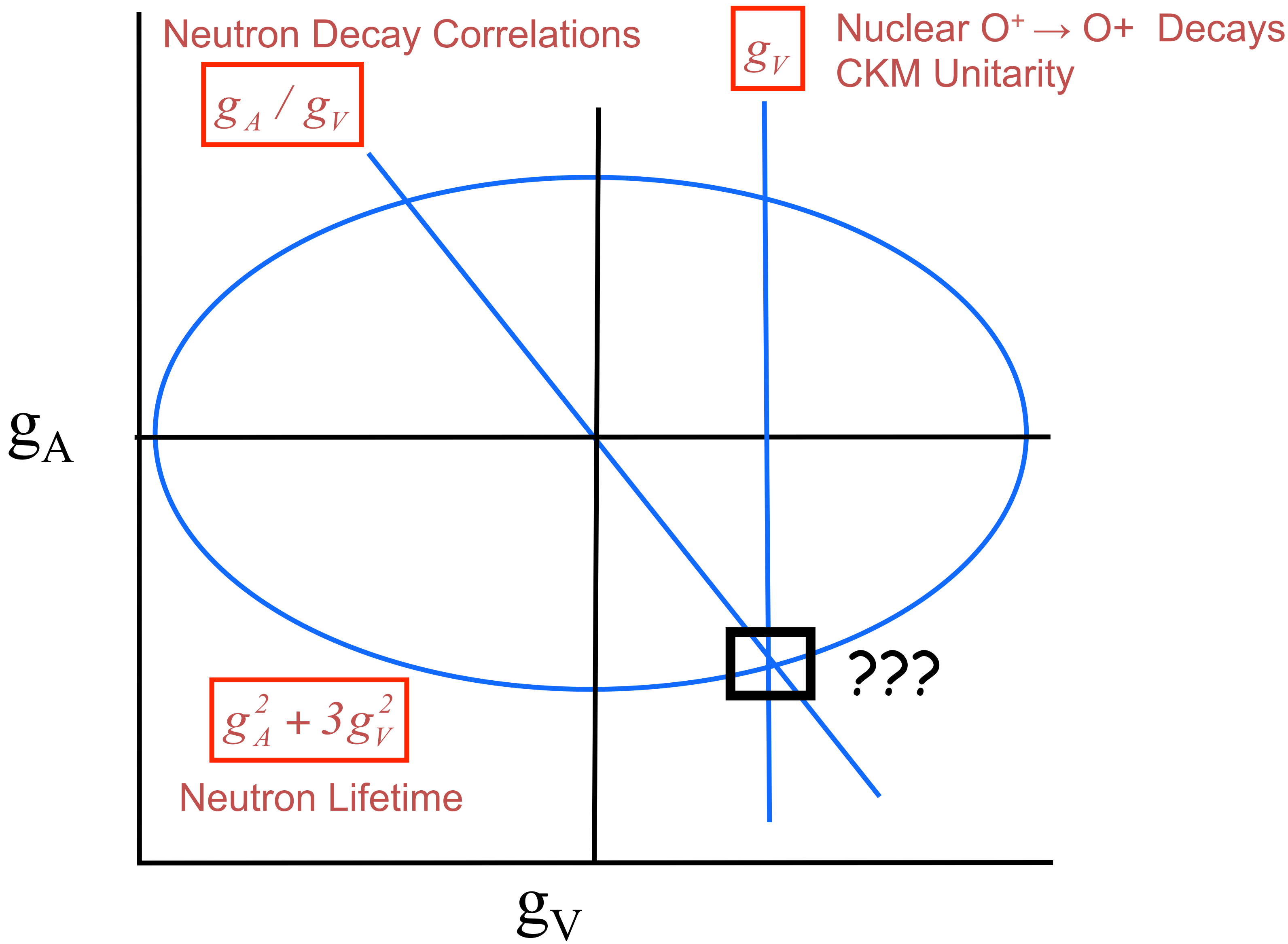
$$\boxed{B = 2\frac{\left(\frac{g_A}{g_V}\right)^2 - \left(\frac{g_A}{g_V}\right)}{1 + 3\left(\frac{g_A}{g_V}\right)^2}}$$

Neutron beta decay measurements give:

$$(g_A^2 + 3g_V^2)$$

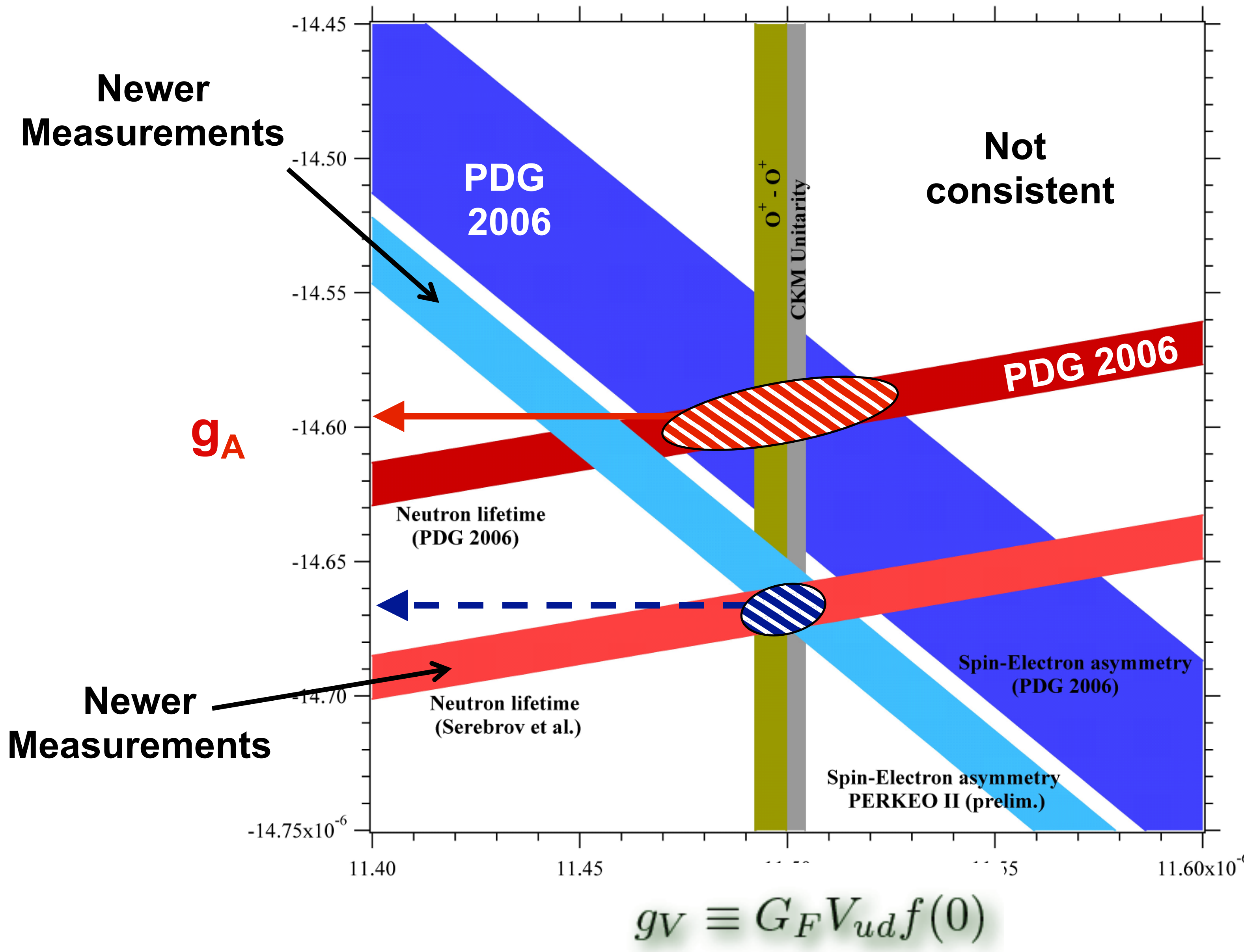
$$g_A / g_V$$

D. Hertzog


Neutron Decay Correlations
g_A / g_V
g_V
Nuclear O⁺ → O+ Decays,
CKM Unitarity
g_A
???
$g_A^2 + 3g_V^2$
Neutron Lifetime
g_V

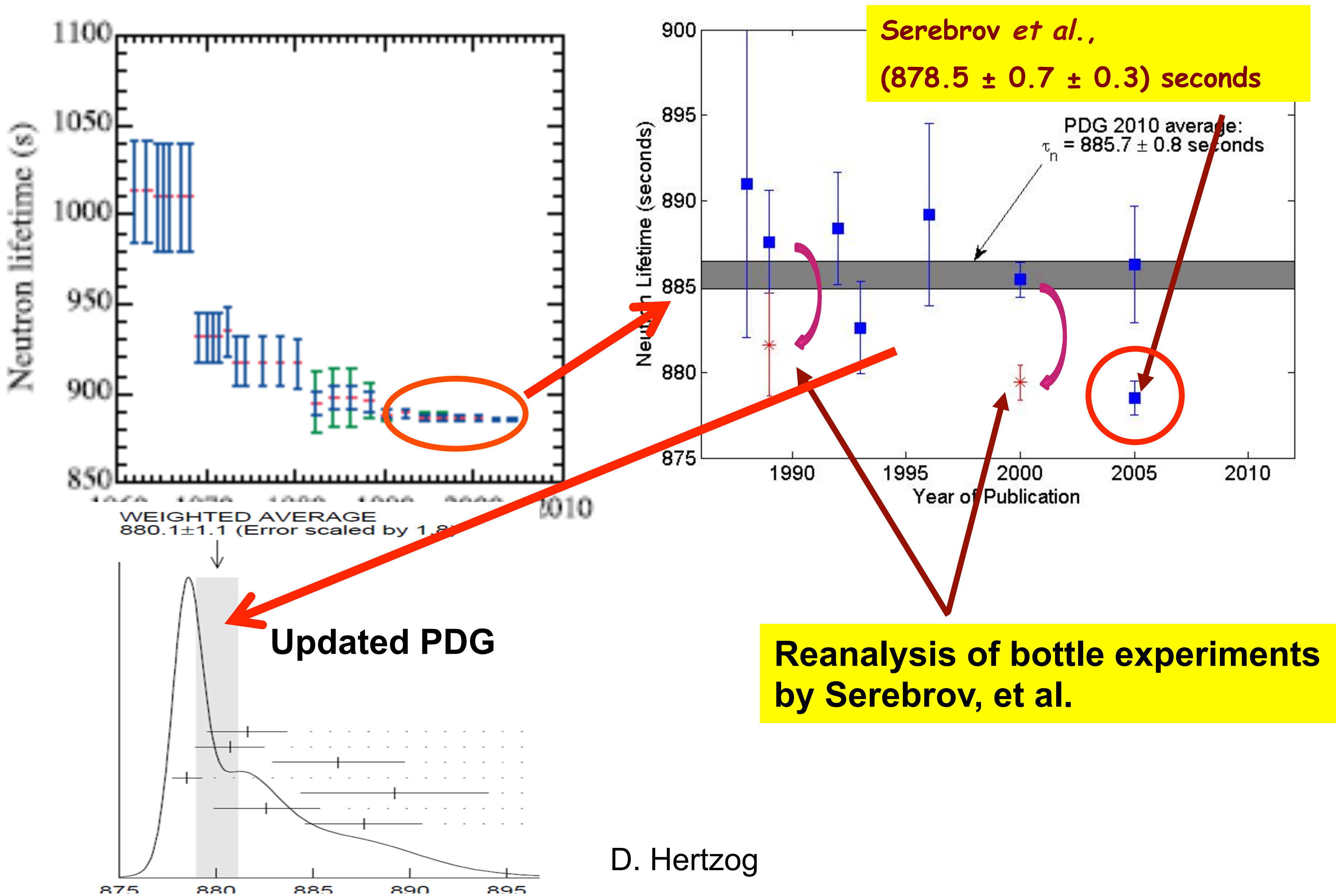
D. Hertzog

2007 picture: Lifetime and Correlations combine in a confused picture for the physics of g_A or unitarity



J. Nico, 2007

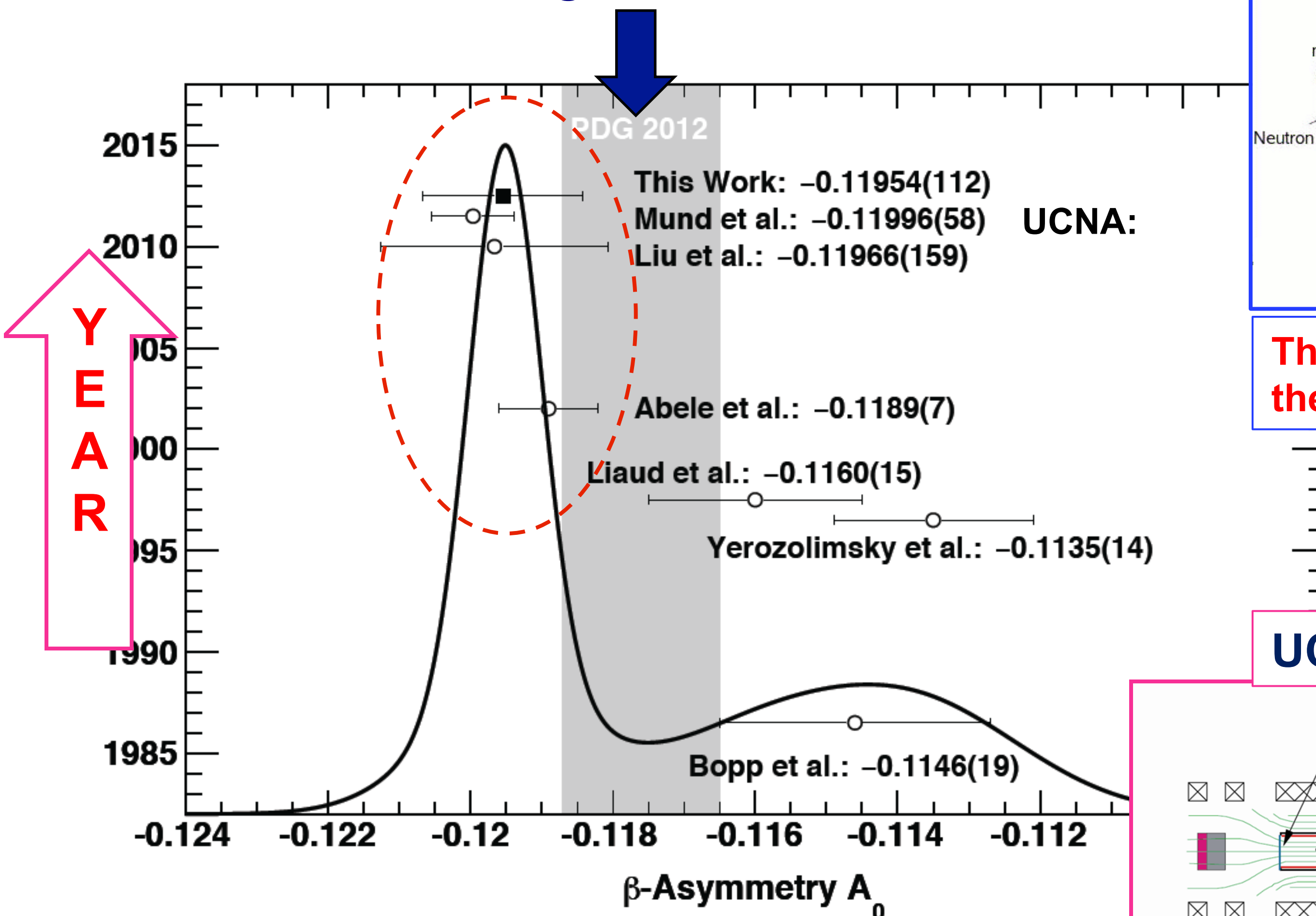
This well-known plot of Neutron Lifetime versus Time illustrates just how difficult this measurement is:



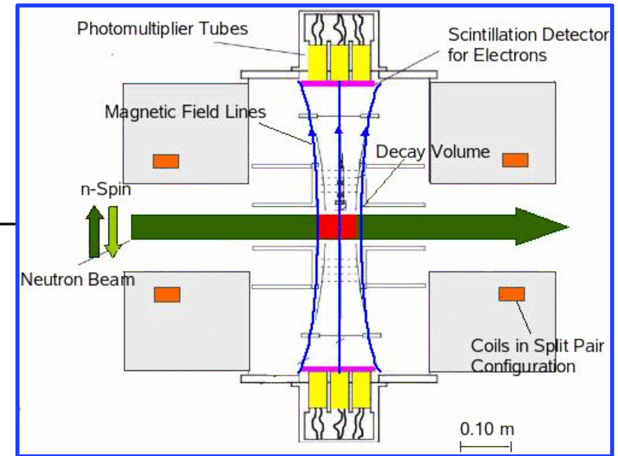
D. Hertzog

2013 Update on beta decay asymmetry

The PDG 2012 is no longer favored

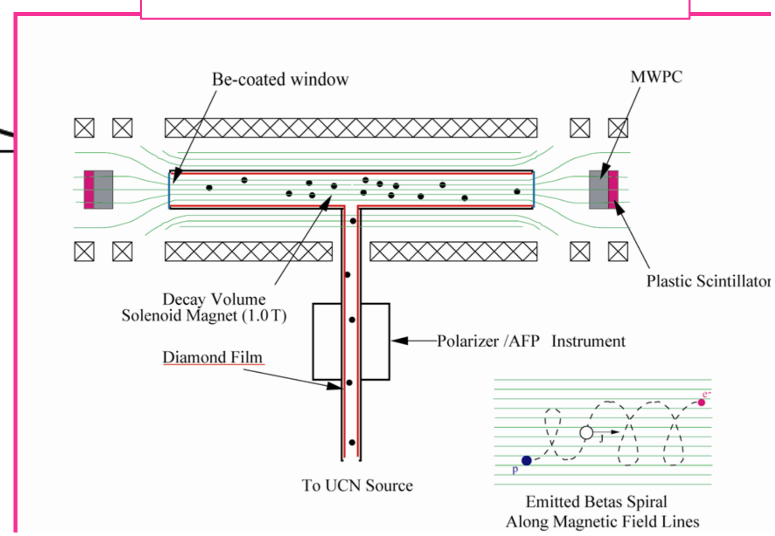


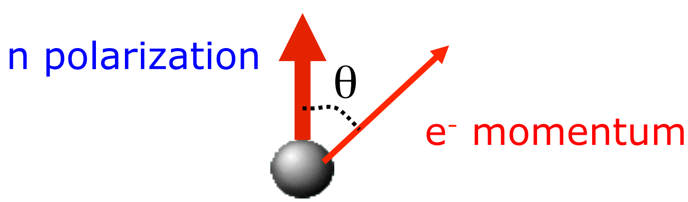
PERKEO II



The ILL efforts have defined the field for a long time

UCNA with ultracold n

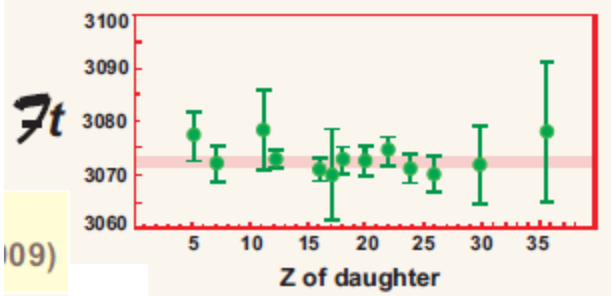




D. Hertzog

2009-12: SUPERALLOWED $0^+ \rightarrow 0^+$ BETA DECAY

$$\mathcal{F}t = ft\,(1+\delta'_R)[1-(\delta_C-\delta_{NS})] = \frac{K}{2G_V^2\,(1+\Delta_R)}$$

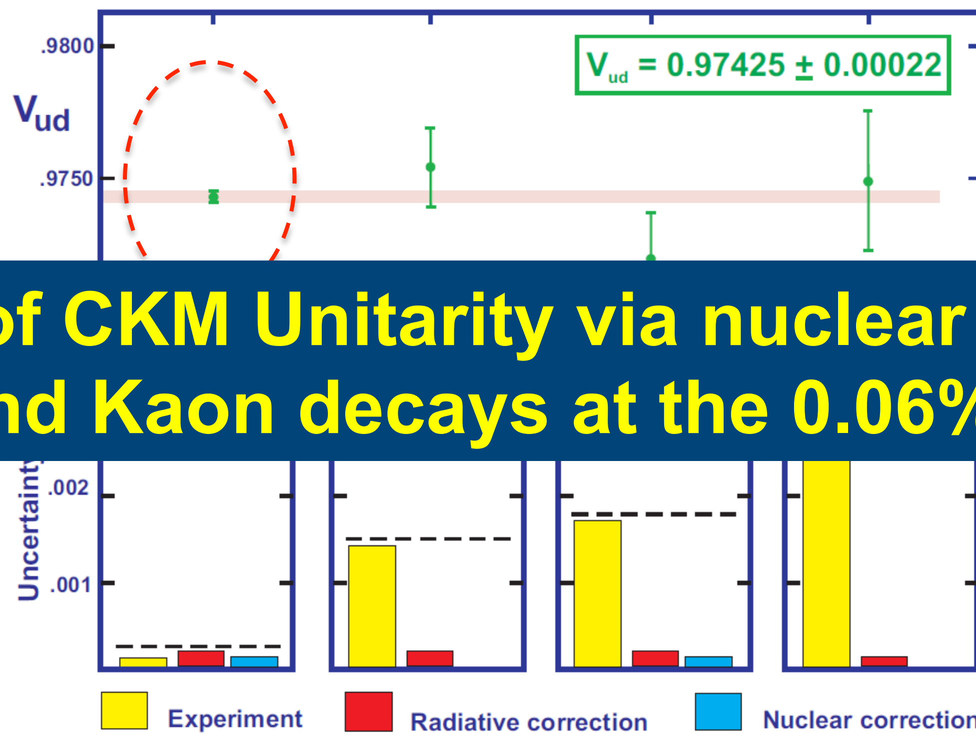


- CVC verified
- V_{ud} = 0.97425(22)

CKM unitarity test:

$V_{ud}^2 + V_{us}^2 + V_{ub}^2$
= 0.9999(6)

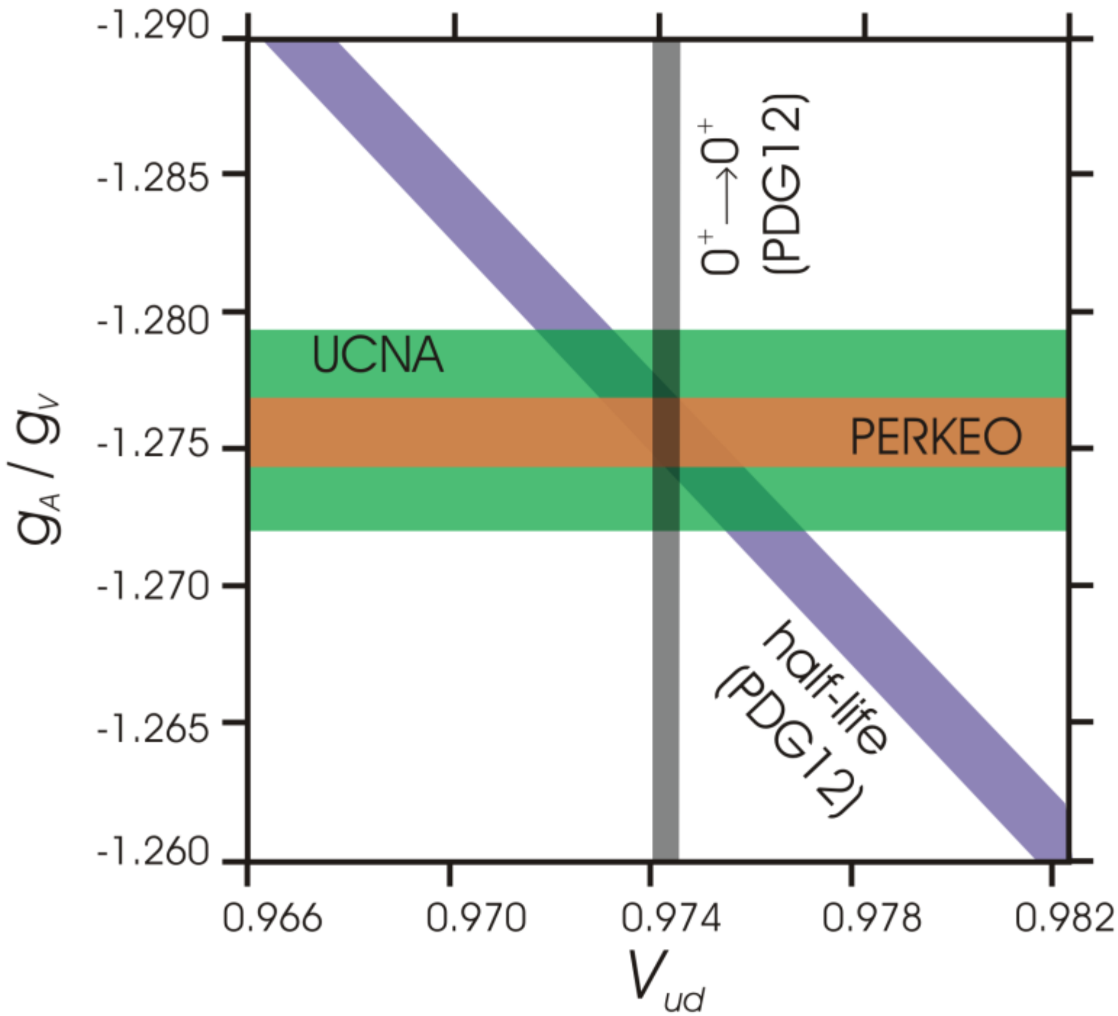
CURRENT STATUS OF V_{ud} – 2012



Tests of CKM Unitarity via nuclear beta, muon and Kaon decays at the 0.06% level

Hardy et al

2013 Picture: Lifetime, Correlations, V_{ud} all painting a very consistent picture now



Mendenhall et al., PRC **87**, 032501 (2013).

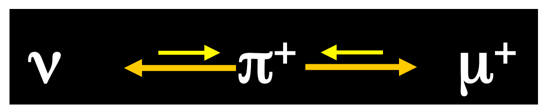
Sorry, this plot is turned and arranged differently

Muon Primer

- **Mass ~ 207 m_e** (50 ppb)
  - $(m_\mu/m_e)^2 \approx$ 43,000 times more sensitive to "new physics" through quantum loops compared to electrons (taus would be better!)

- **Lifetime ~2.2 μs** (1 ppm)
  - High-intensity beams; can stop and study; can possibly collide

- **Primary production: $\pi^+ \rightarrow \mu^+\nu_\mu$** (99.98%)
  - Polarized naturally:



- **Primary decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$** (~99%)
  - Purely weak; distribution in θ and *E* reveals weak parameters

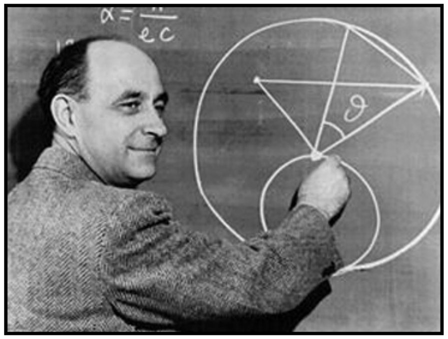
- **Lepton number is conserved**

  (BRs < 10^{-12})

$$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$$

D. Hertzog

Muon Lifetime

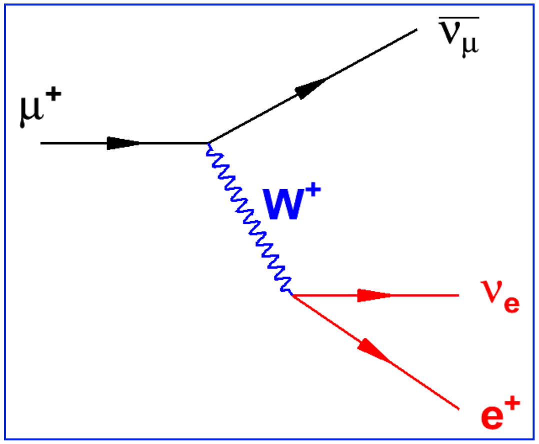


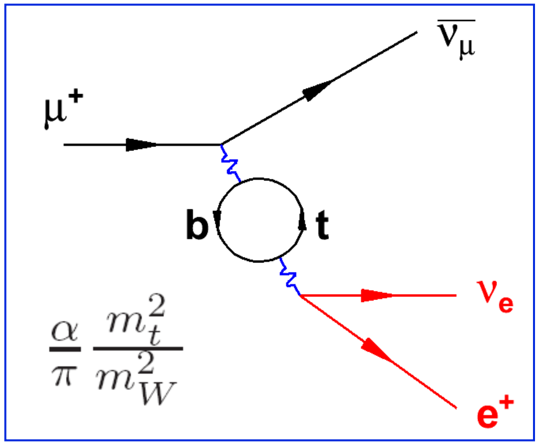
Fundamental electro-weak couplings

G_F	α	M_Z
15 ppm → 0.5 ppm	0.37 ppb	23 ppm

Implicit to all EW precision physics

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1+\Delta r(m_t, m_H, \ldots)\right)$$

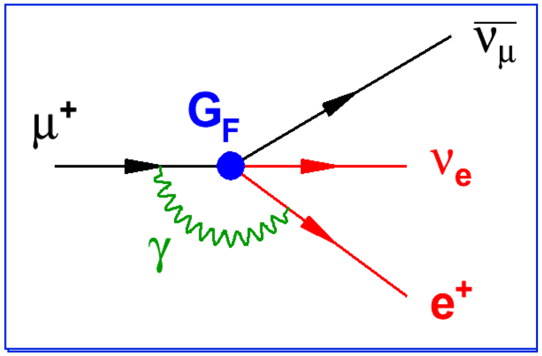




Uniquely defined by muon decay

$$\frac{1}{\tau_{\mu^+}} = \frac{G_F{}^2 m_\mu^5}{192\pi^3}(1+q)$$

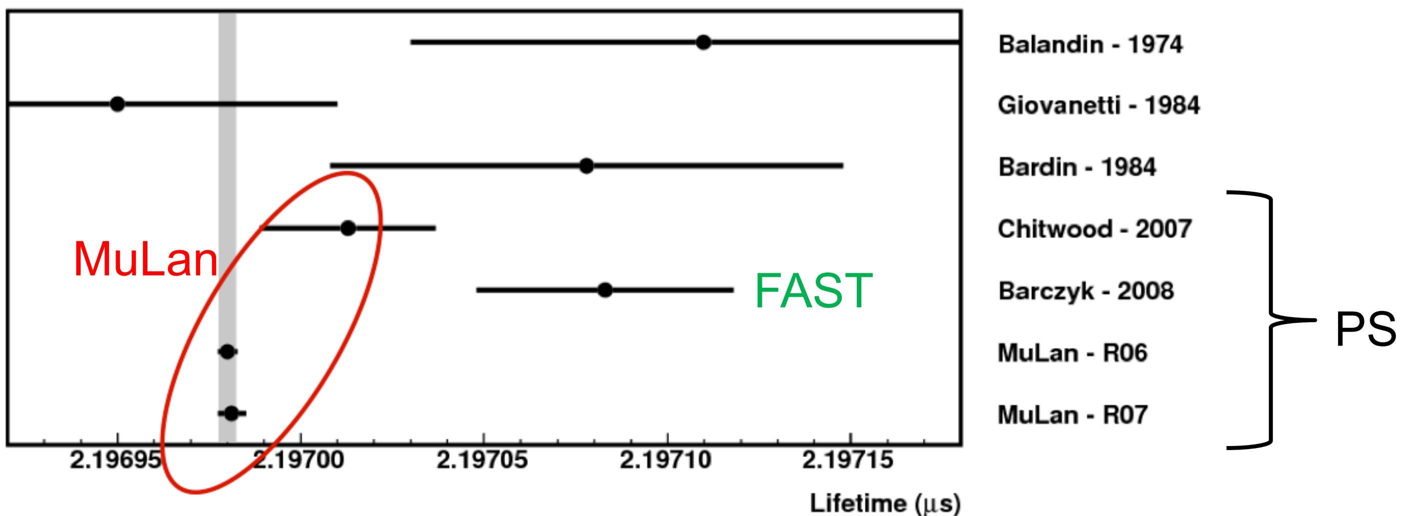
QED



Extraction of G_F from τ_μ :
reduced error from
15 to ~0.2 ppm

D. Hertzog

Final Results: Muon lifetime & Fermi constant



The most precise particle or nuclear or atomic lifetime ever measured

τ(R06) = 2 196 979.9 ± 2.5 ± 0.9 ps
τ(R07) = 2 196 981.2 ± 3.7 ± 0.9 ps

τ(Combined) = 2 196 980.3 ± 2.2 ps (1.0 ppm)
$\Delta\tau$(R07 – R06) = 1.3 ps

New G_F (30x improved since 1999 PDG)

G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)

PRL 106, 041803 (2011)
Phys. Rev. D 87, 052003 (2013)


InsideScience.org
Inside Science News Service
FEBRUARY 11, 2011

Additional content is available to registered journalists: More info >

Research

Text size: Print E-mail this story BOOKMARK Tweet 3

Weak Nuclear Force Is Less Weak

New insights from subatomic particles that fly apart.

Jan 12, 2011

By Phillip F. Schewe
Inside Science News Service

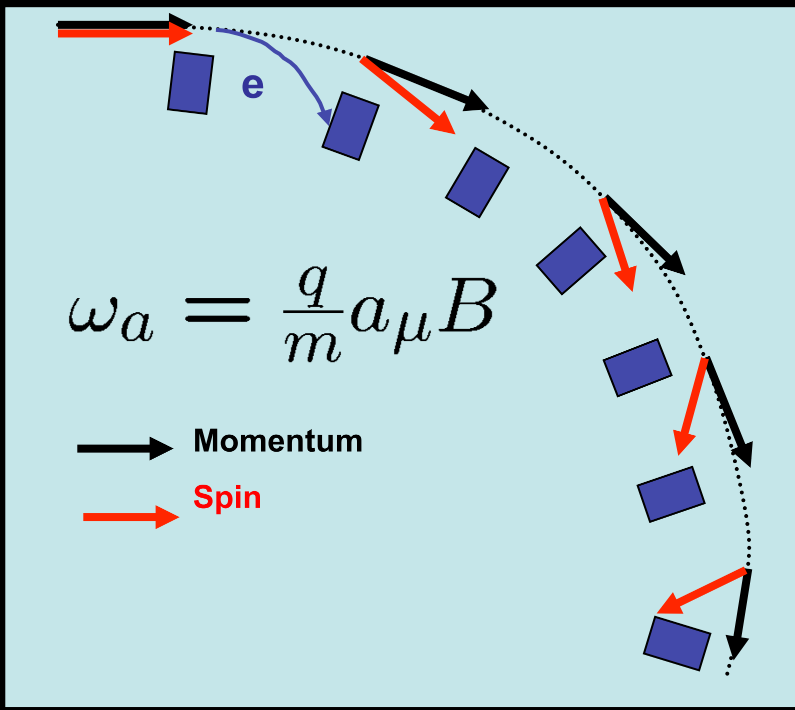
(ISNS) -- The force that governs some of the reactions that keep our sun shining is not quite as weak as scientists had previously thought. As a consequence, our estimation of how energetic the sun actually is just went up by a tiny amount.

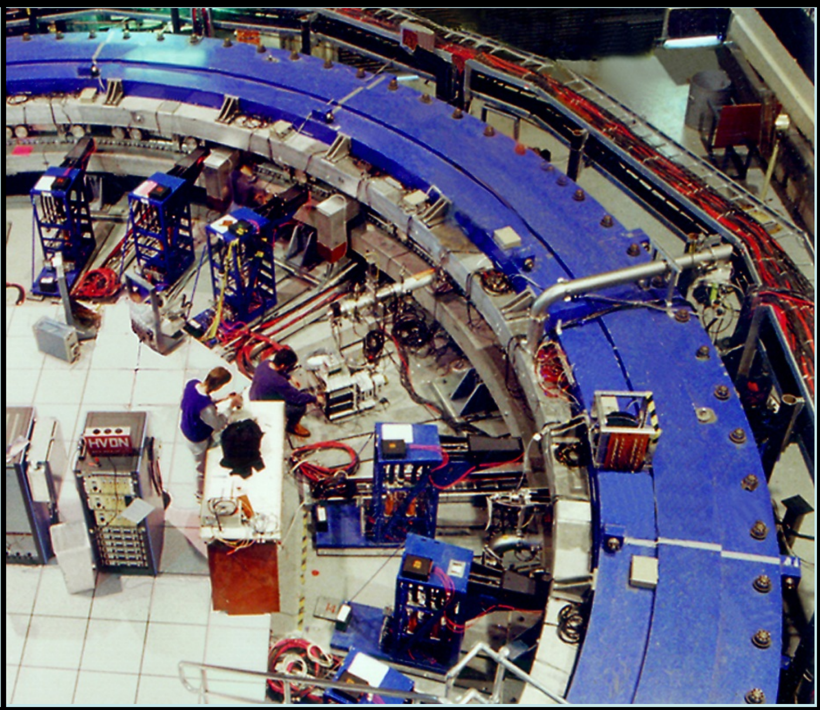
The evidence for this weak nuclear force comes from the decay of muons, essentially heavier cousins of the electron, one of the building blocks of atoms.

Just as biologists sometimes study the tiniest and most

View full-size image

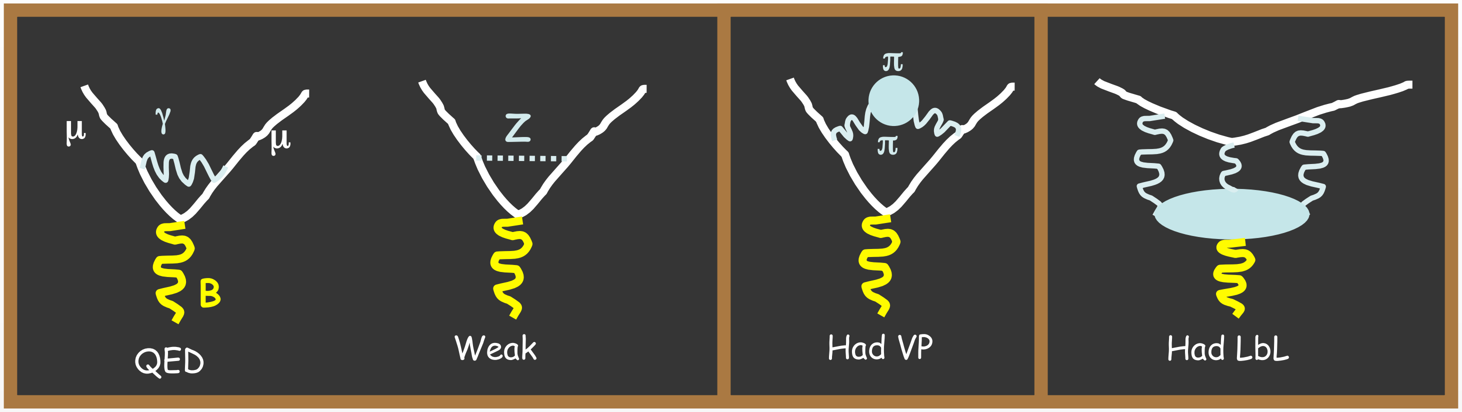
Is the muon g-2 signal a sign of new physics?





$$a_\mu\left(\text{Expt.}\right)=116592089\left(63\right)\times10^{-11} \qquad \left(0.54\ \text{ppm}\right)$$

a_μ = (g – 2)/2 can be calculated very precisely



Known well **Theoretical work ongoing**

Contribution	Result ($\times 10^{-11}$) units
QED (leptons)	$116\ 584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 914 \pm 42_{\text{exp}} \pm 14_{\text{rad}} \pm 7_{\text{pQCD}}$
HVP(ho)	$-98 \pm 1_{\text{exp}} \pm 0.3_{\text{rad}}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\ 591\ 793 \pm 51$

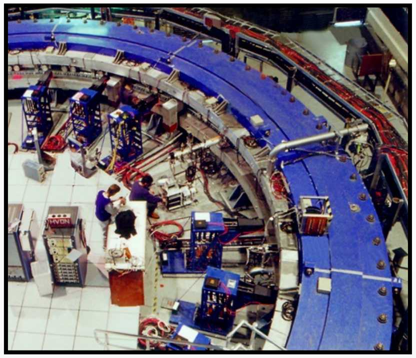
Hadrons !

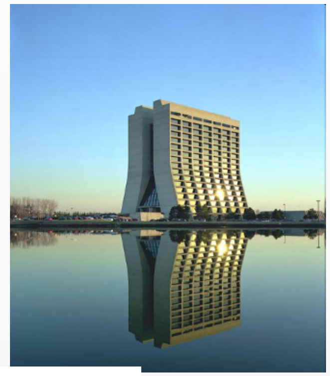
The "g-2 test": Compare experiment to theory. Is SM complete?

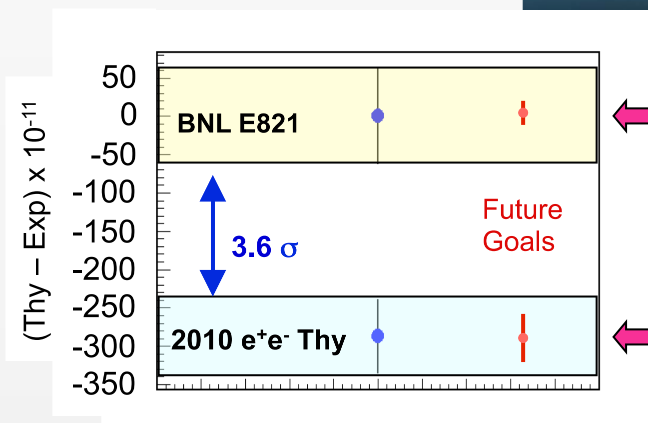
$$\delta a_\mu^{NewPhysics} = a_\mu^{Expt.} - a_\mu^{Theory}$$

D. Hertzog

A New Muon g-2 Experiment at Fermilab







Goal: 0.14 ppm

Expected Improvement

Approved E989:	Jan, 2011
CD-0:	Sept 2012
Independent Design Review:	May 2013
CD-1: (Scheduled)	Sept. 2013

$\Delta a_\mu(\text{Expt} - \text{Thy}) = 297 \pm 81 \times 10^{-11}$ 3.6 σ

Ground-breaking last month

MC-1 Building

Home of the
Muon g-2 Experiment

Architect:
Middough

Subcontractor:
Whittaker Construction
and Excavating, Inc.

Fermi Research Alliance LLC

U.S. DEPARTMENT OF ENERGY | Office of Science

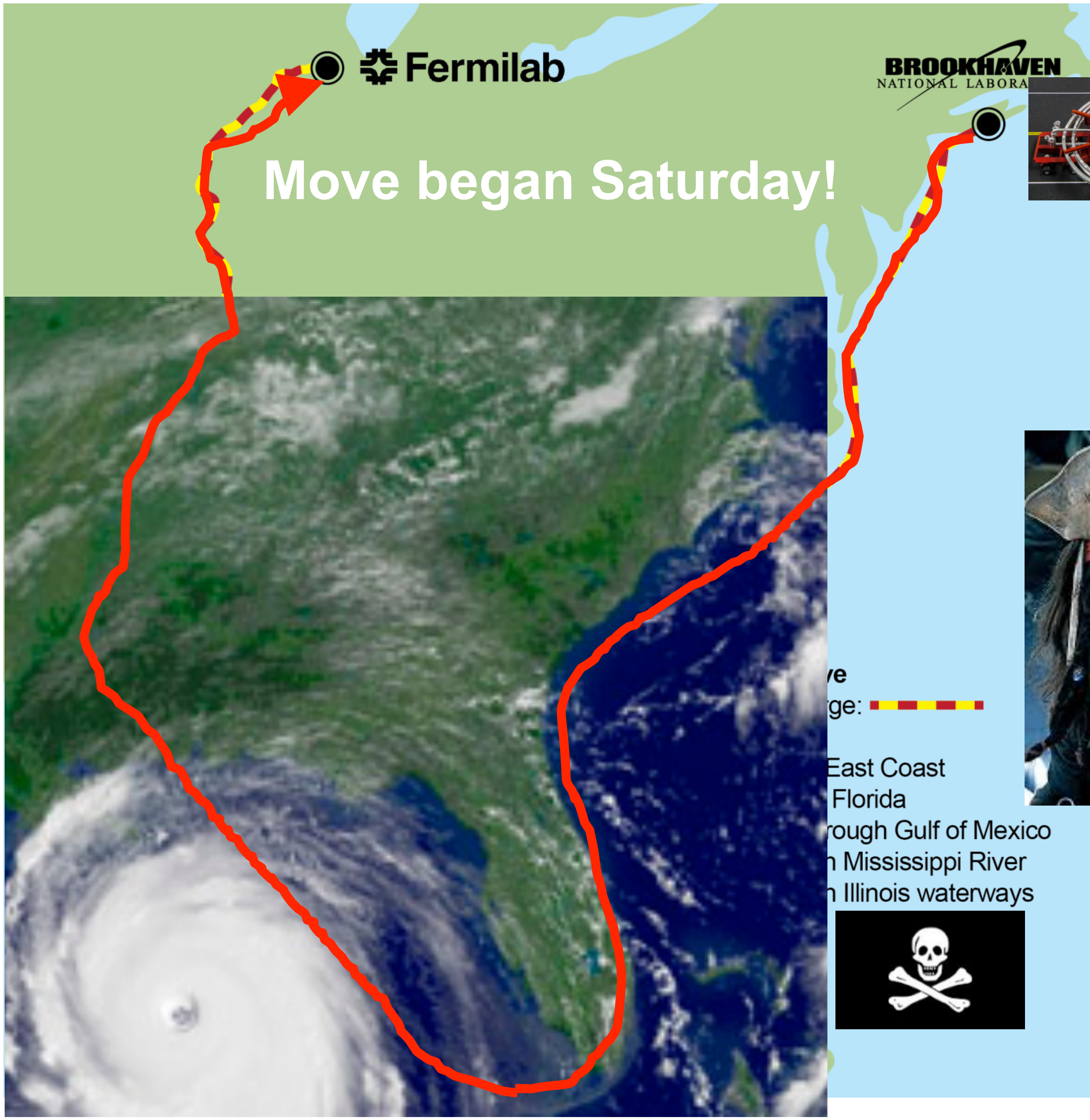
The Muon Campus

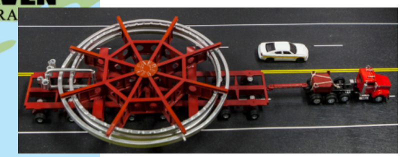
Fermilab

May 8, 2013

June 18, 2013

Beware of Pirates and Hurricanes





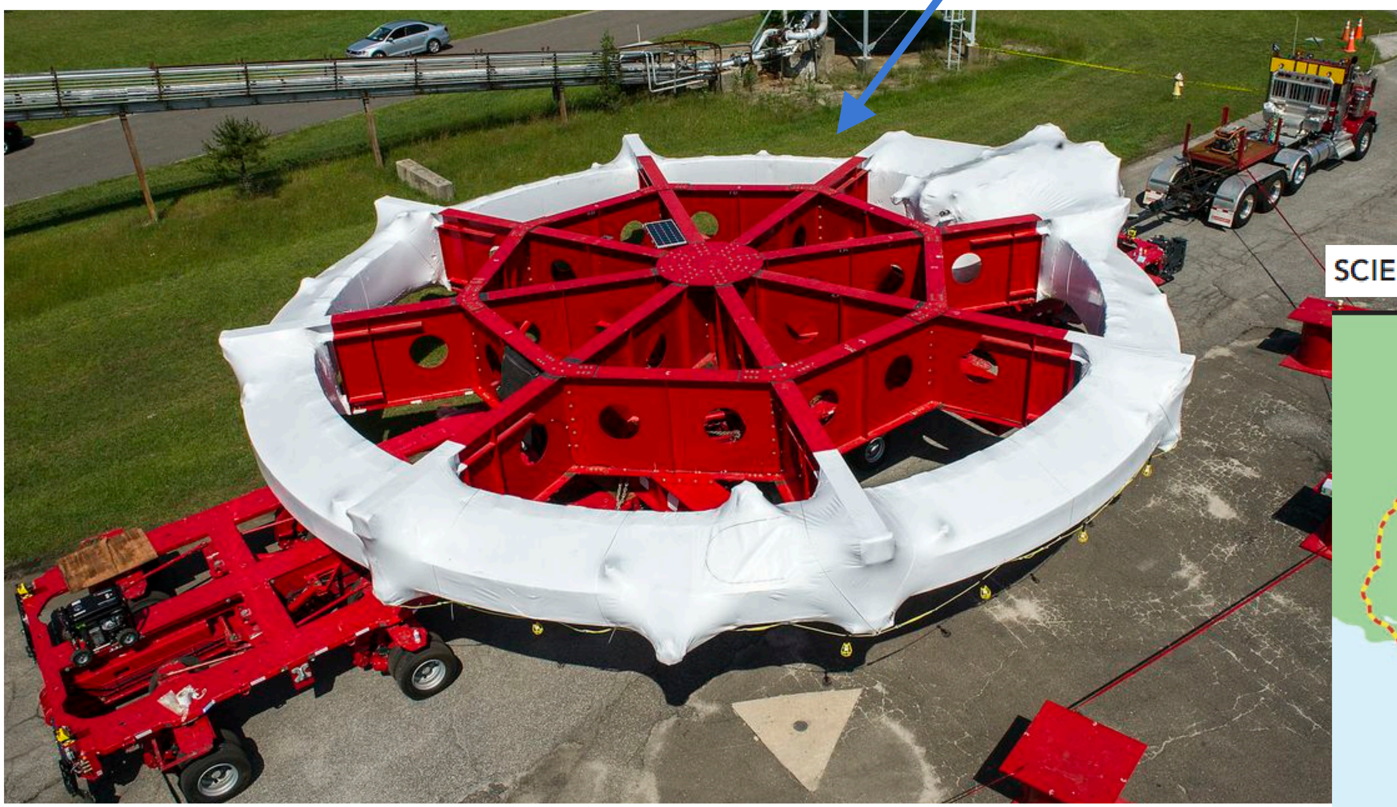
D. Hertzog

Moving the storage ring has begun

SCIENTIFIC AMERICAN™

Honk If You Love Muons: 3,200 Mile Road Trip Planned For Muon G-2 Storage Ring

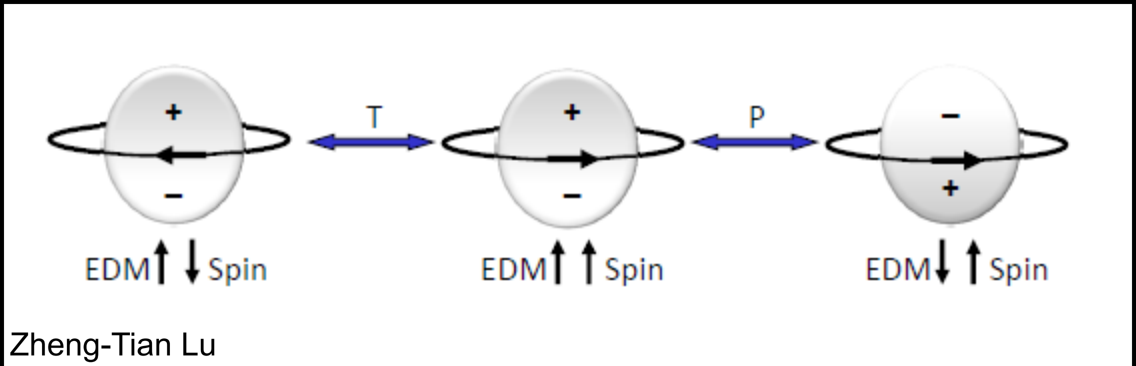
If you're driving from New York to Illinois this summer and you find yourself getting really annoyed because you're crawling behind a slow truck with an oversize load, check out that load.



SCIENCE VOL 340 14 JUNE 2013

Circuitous. Researchers chose a long sea-and-river route for relocating a massive but delicate storage ring (*below*) from Brookhaven National Lab to Fermilab.

Permanent Electric Dipole Moments
(This field is big enough it has its own conferences)



EDM violates T → violates CP

New sources of CP → BAU ?

Experiments are largely the same:
Precess spin in B field with parallel and anti-parallel E
Measure the frequency difference

Lessons and Promise of Low-Energy Precision Physics

- **The Standard Model is tough to crack**
- **Direct energy frontier experiments are the obvious way to explore …**
  - **But they can run out of resolution (kinematics)**
  - **And may not fully define the physics behind the finding**
- **High precision – in well selected efforts – can often reach beyond through loops**
  - **And, these observables will provide complementary clues about the nature of any new discoveries**

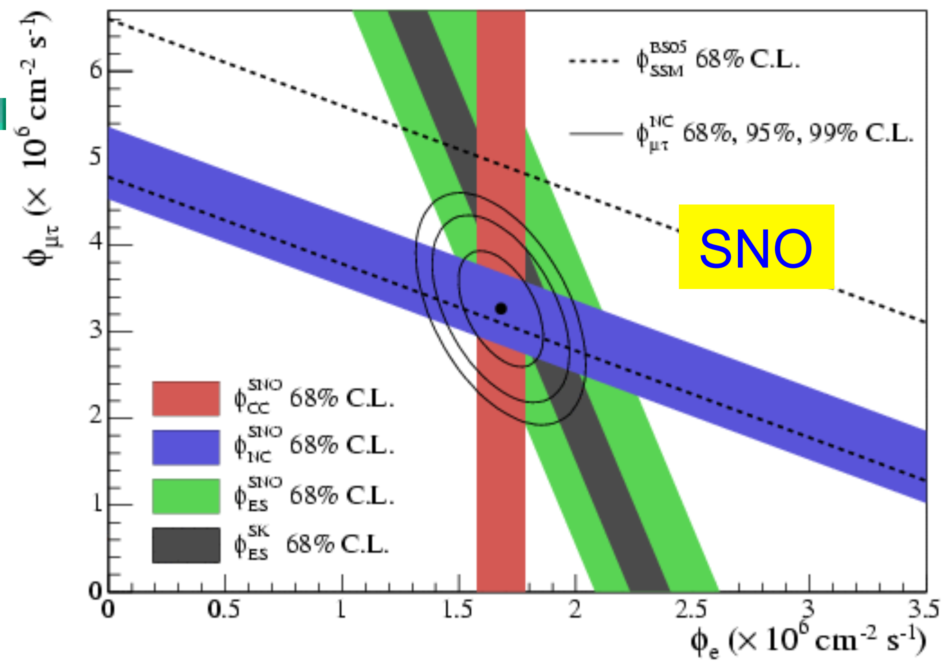
D. Hertzog

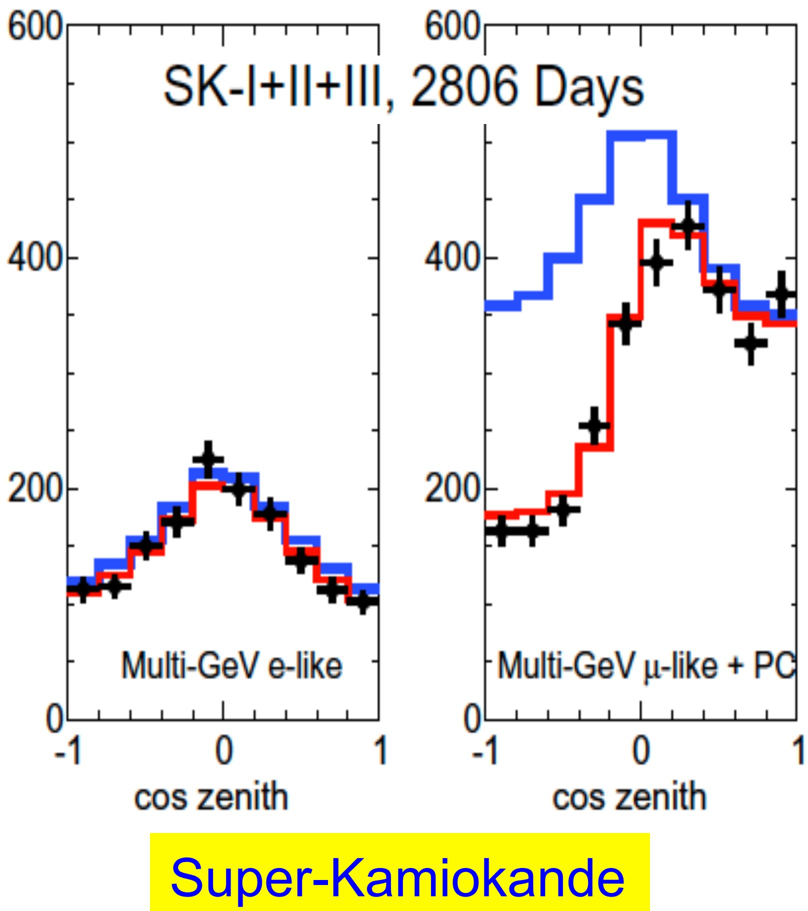
Neutrinos

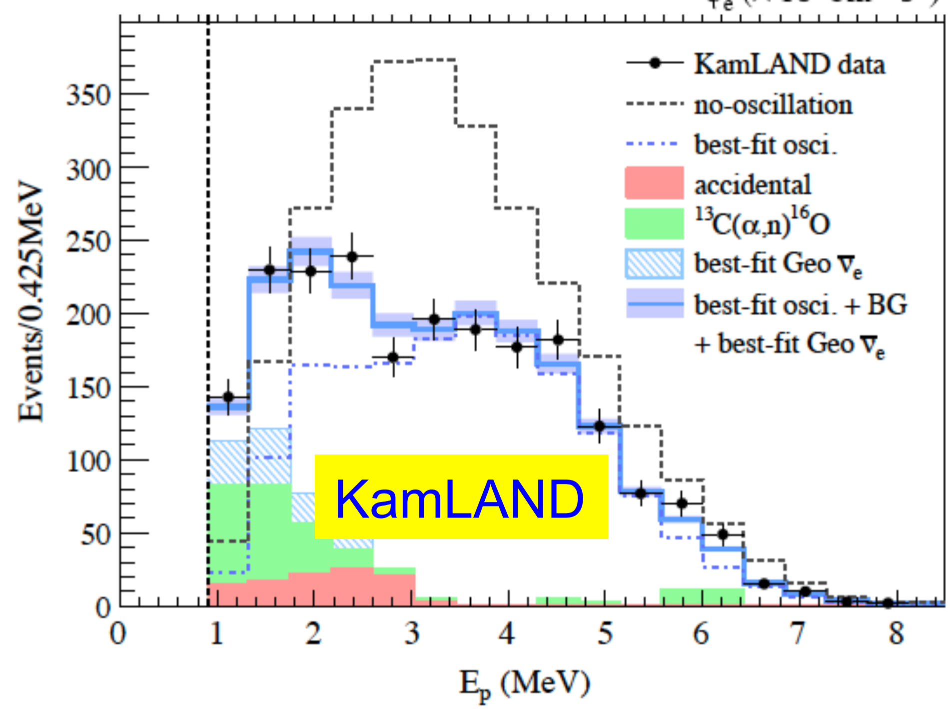
The big questions

- 1. Major scientific discoveries since 2007
  - θ_{13} measured!
  - Higgs found!
  - Borexino, SNO, SK, KamLAND results
  - MiniBooNE results
  - Nuclear theory of DBD
  - EXO and KamLAND results for ^{136}Xe $2\nu\beta\beta$, $0\nu\beta\beta$
  - Idea to use cyclotron radiation for neutrino mass measurement, “Project 8”.

Neutrinos oscillate, have mass







The MNSP Mixing Matrix and oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Unitary matrix: 9 parameters not all independent.

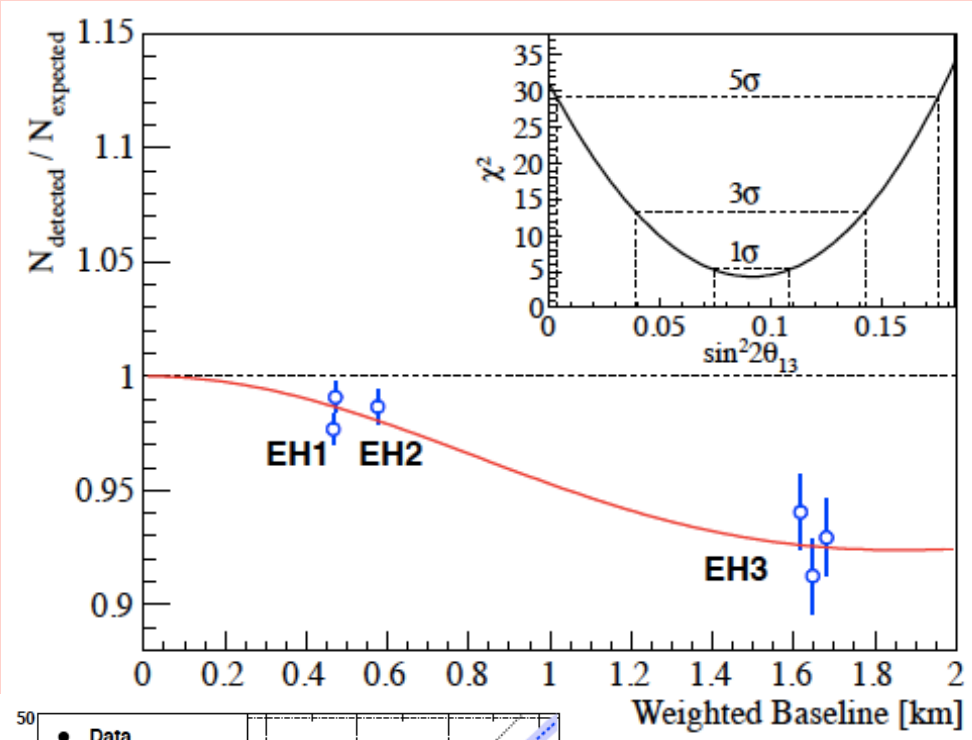
3 trig angles enough to describe oscillations. There are also CP-violating phase(s).

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

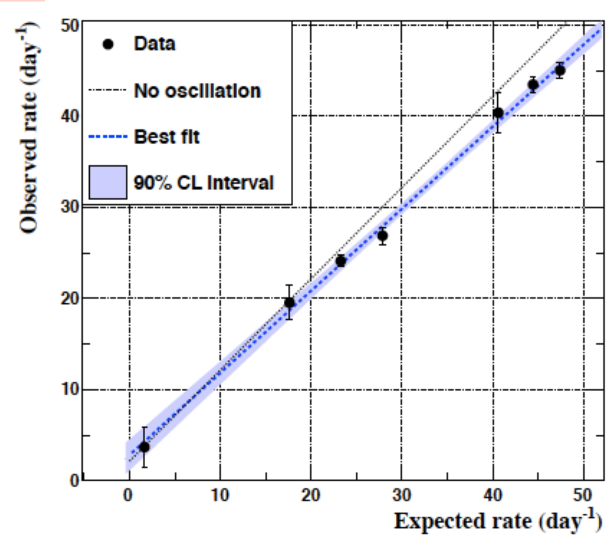
$$\lambda = \frac{h}{p} \qquad p_i - p_j \approx (m_j^2 - m_i^2)\frac{L}{2E}$$

Depends on **mass-squared differences** × **distance**, & the **sizes of the U_{ei}**

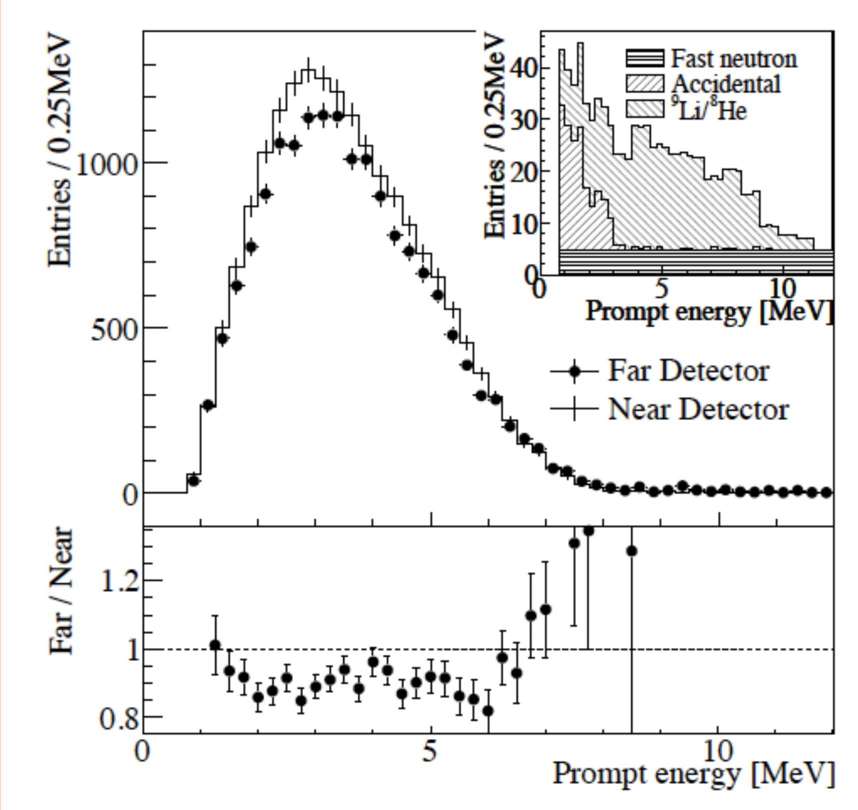
Θ_{13} Measured!



Daya Bay



Double Chooz



RENO

Mass and mixing parameters

	Oscillation	Kinematic
$\Delta m_{21}{}^2$	$7.54^{+0.21}_{-0.21} \times 10^{-5}$ eV^2	
$\lvert\Delta m_{32}{}^2\rvert$	$2.42^{+0.12}_{-0.11} \times 10^{-3}$ eV^2	
Σm_i	> 0.055 eV (90% CL)	< 5.4 eV (95% CL)*
θ_{12}	$34.1^{+0.9}_{-0.9}$ deg	
θ_{23}	$39.2^{+1.8}_{-1.8}$ deg	
θ_{13}	$9.1^{+0.6}_{-0.7}$ deg	
$\sin^2\theta_{13}$	$0.025^{+.003}_{-.003}$	

Marginalized 1-D 1-σ uncertainties.

*C. Kraus et al., Eur. Phys. J. C40, 447 (2005); V. Aseev et al. PRD in press.
Other refs, see Fogli et al. 1205.5254

What do we still want to know?

Are neutrinos their own antiparticles?

Do neutrinos violate CP?

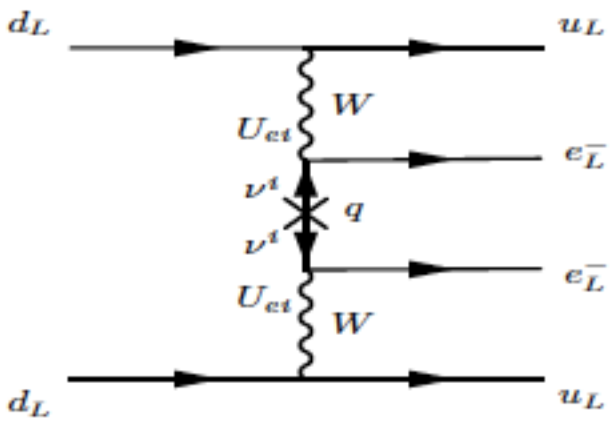
What is the mass?

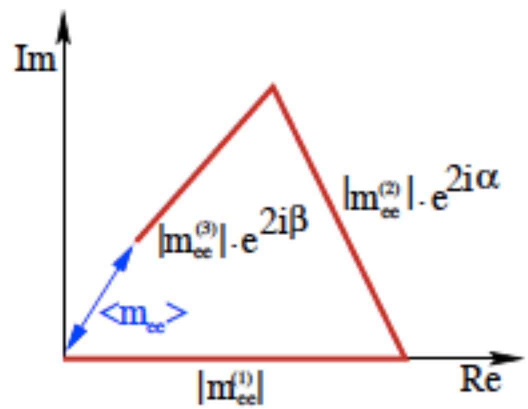
What is the level ordering (hierarchy)?

And many other things…

Neutrinoless Double Beta Decay

Are neutrinos their own antiparticles?
Is lepton number conserved?





W. Rodejohann, 1206.2560

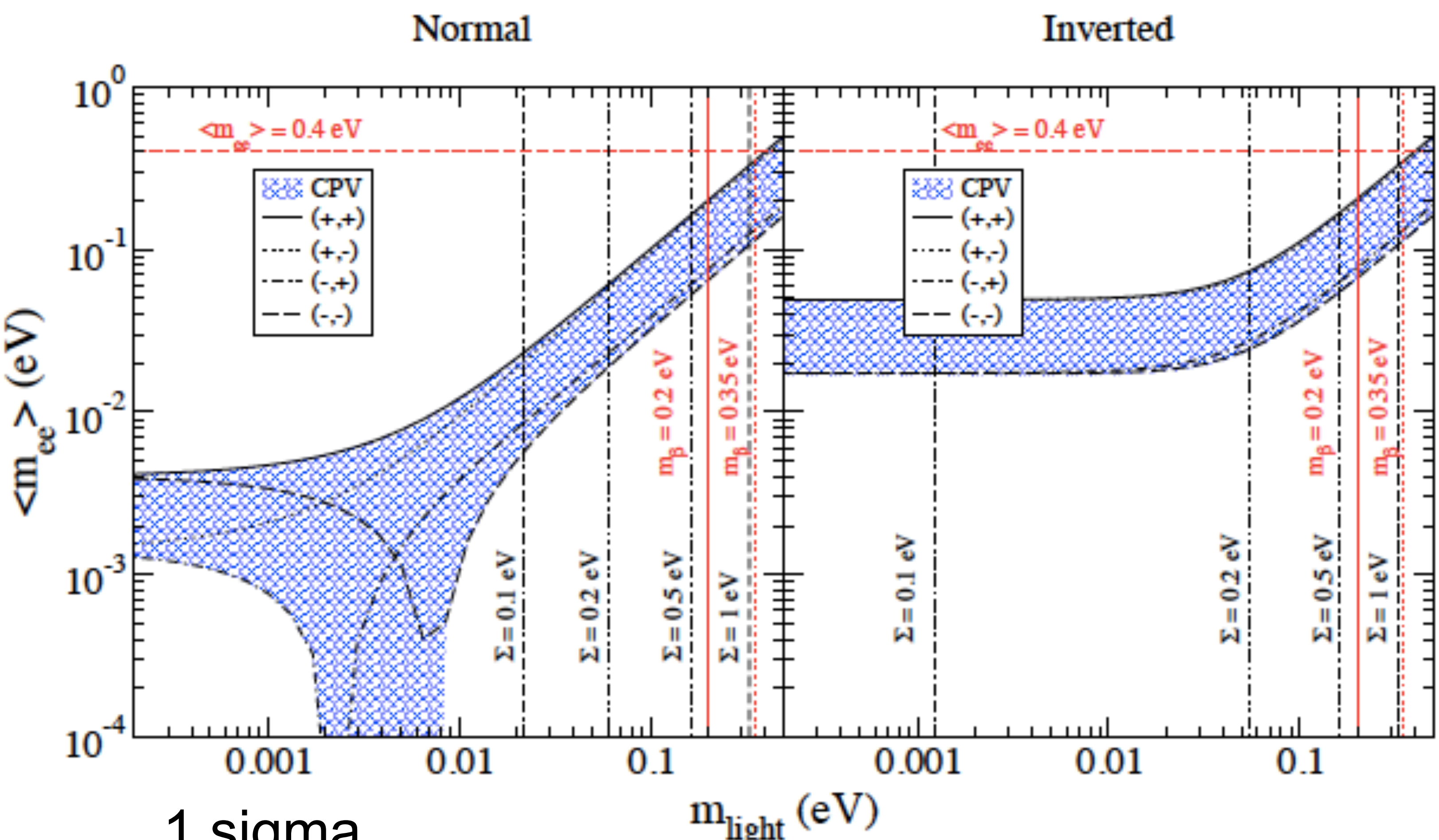
Decay rate per unit mass:

$$\lambda_{0\nu} \frac{N}{M} = \frac{\ln(2) N_A}{A m_e^2} G_{0\nu}^{(0)} g_A^4 |M_{0\nu}|^2 |\langle m_{ee} \rangle|^2$$

$$\equiv \Gamma_{0\nu} \, |M_{0\nu}|^2 \, |\langle m_{ee} \rangle|^2$$

$$\langle m_{ee} \rangle = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta} \right|$$

Neutrinoless Double Beta Decay



1 sigma

W. Rodejohann, 1206.2560

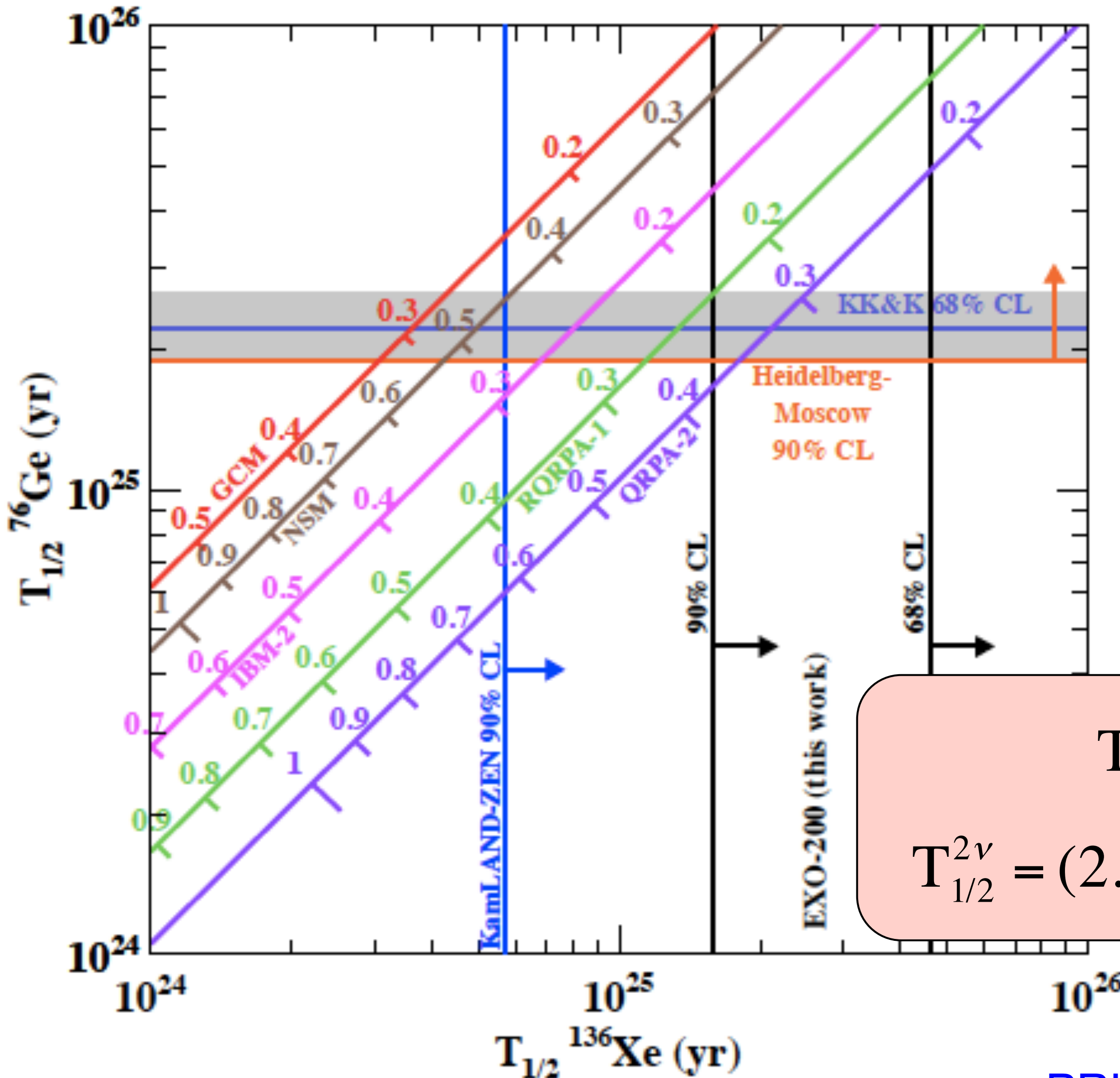
Large-scale experiments

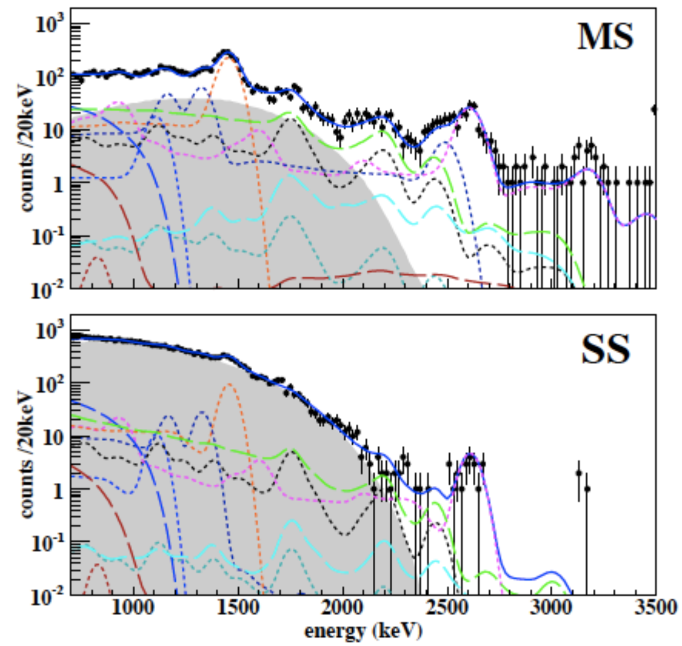
Table 4. Details of the most advanced experiments. Given are life-time sensitivity and the expected limit on $\langle m_{ee} \rangle$, using the NME compilation from figure 5.

Experiment	Isotope	Mass [kg]	Sensitivity $T_{1/2}^{0\nu}$ [yrs]	Status	Start of data-taking	Sensitivity $\langle m_\nu \rangle$ [eV]
GERDA	^{76}Ge	18	3×10^{25}	running	~ 2011	0.17-0.42
		40	2×10^{26}	in progress	~ 2012	0.06-0.16
		1000	6×10^{27}	R&D	~ 2015	0.012-0.030
CUORE	^{130}Te	200	$6.5 \times 10^{26*}$	in progress	~ 2013	0.018-0.037
			$2.1 \times 10^{26**}$			0.03-0.066
MAJORANA	^{76}Ge	30-60	$(1-2) \times 10^{26}$	in progress	~ 2013	0.06-0.16
		1000	6×10^{27}	R&D	~ 2015	0.012-0.030
EXO	^{136}Xe	200	6.4×10^{25}	running	~ 2011	0.073-0.18
		1000	8×10^{26}	R&D	~ 2015	0.02-0.05
SuperNEMO	^{82}Se	100-200	$(1-2) \times 10^{26}$	R&D	~ 2013-15	0.04-0.096
KamLAND-Zen	^{136}Xe	400	4×10^{26}	running	~ 2011	0.03-0.07
		1000	10^{27}	R&D	~ 2013-15	0.02-0.046
SNO+	^{150}Nd	56	4.5×10^{24}	in progress	~ 2012	0.15-0.32
		500	3×10^{25}	R&D	~ 2015	0.06-0.12

W. Rodejohann, 1206.2560

EXO measures ^{136}Xe 2νββ, limits 0νββ



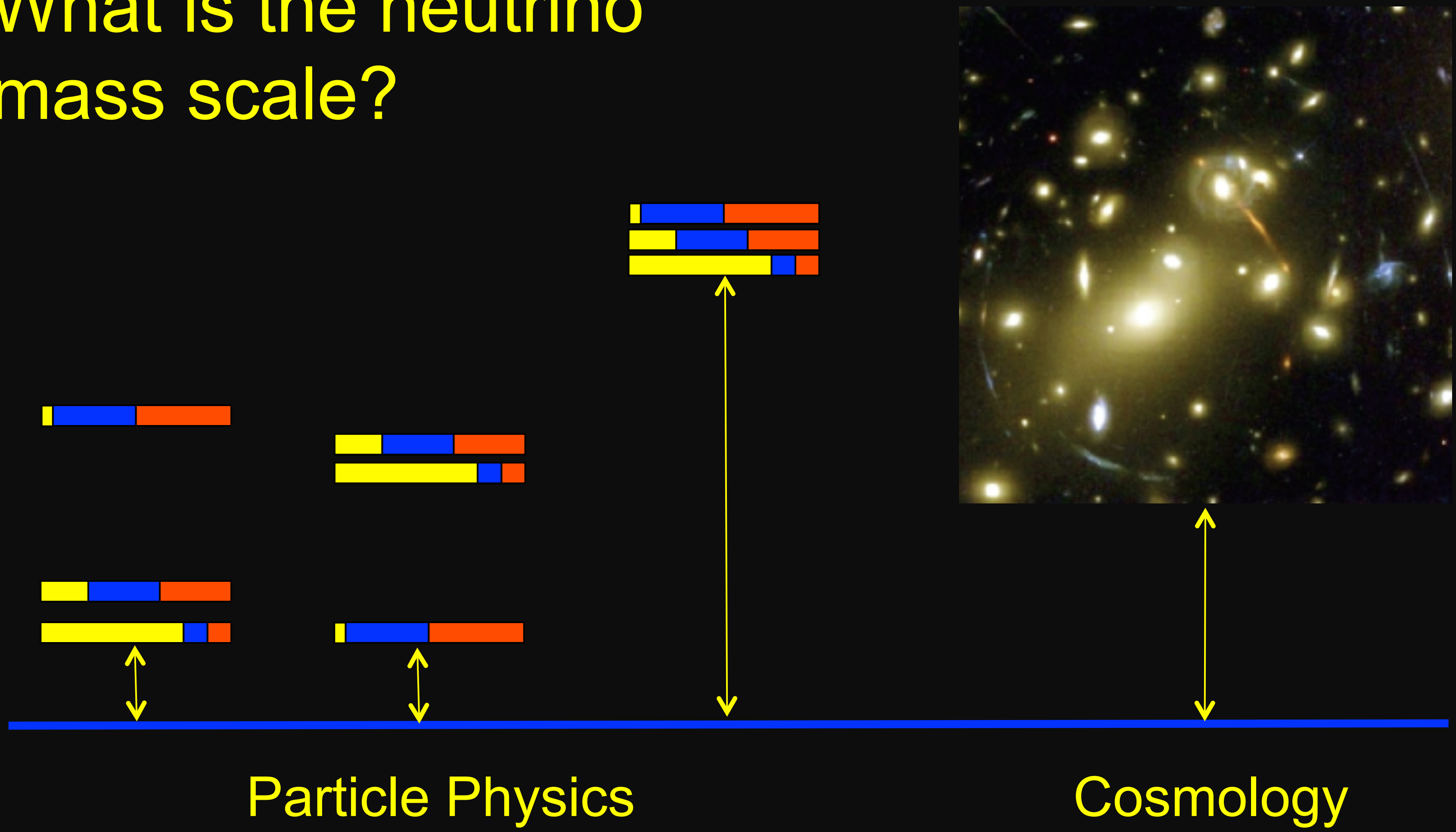


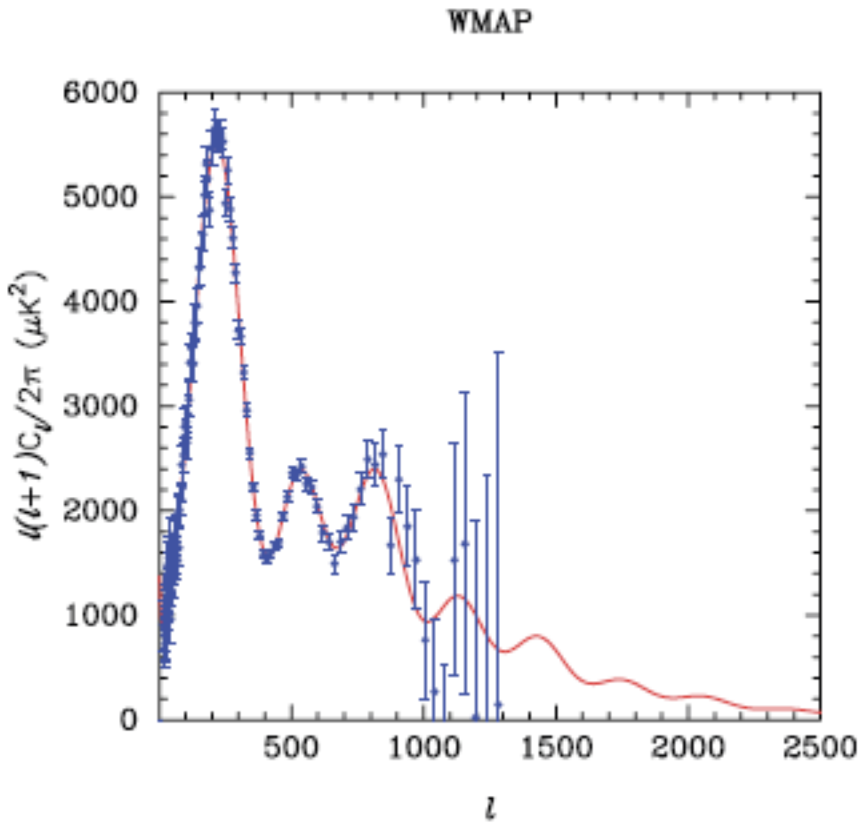
$$T_{1/2}^{0\nu} \geq 1.6 \times 10^{25} \text{ yr}$$

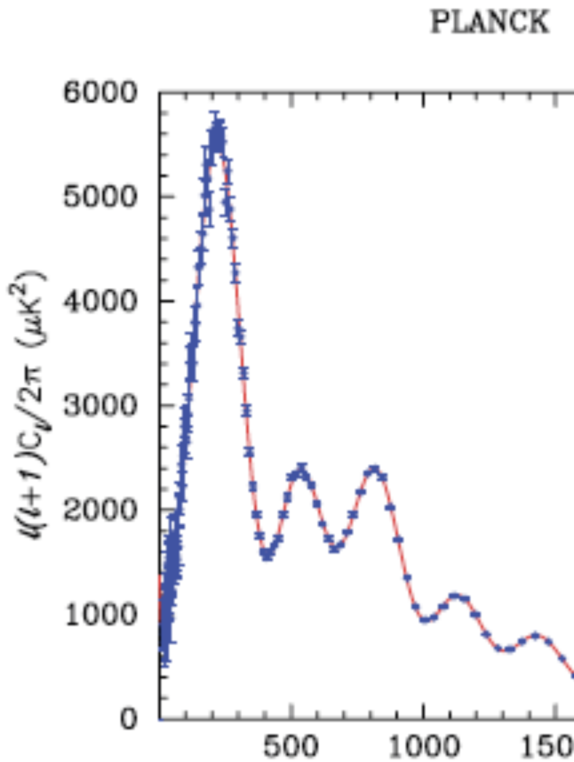
$$T_{1/2}^{2\nu} = (2.23 \pm 0.017 \pm 0.22) \times 10^{21} \text{ yr}$$

PRL 109, 032505 (2012)

What is the neutrino mass scale?





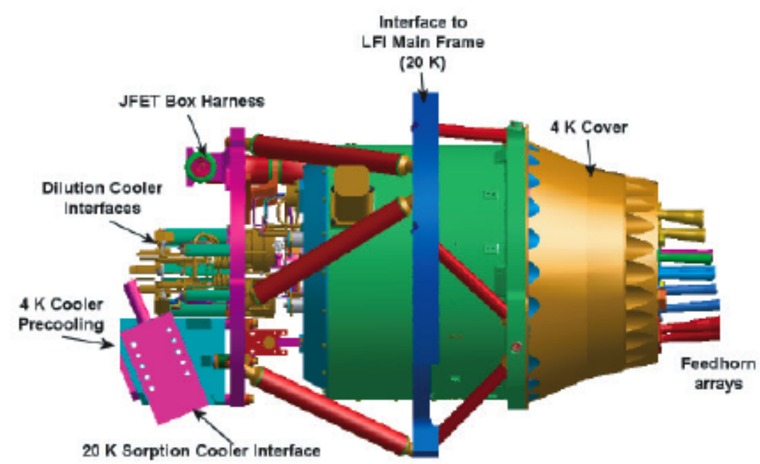


Planck
Launched
May 15, 2009

Present ΛCDM constraints on Σm_ν:
~ 0.6 eV

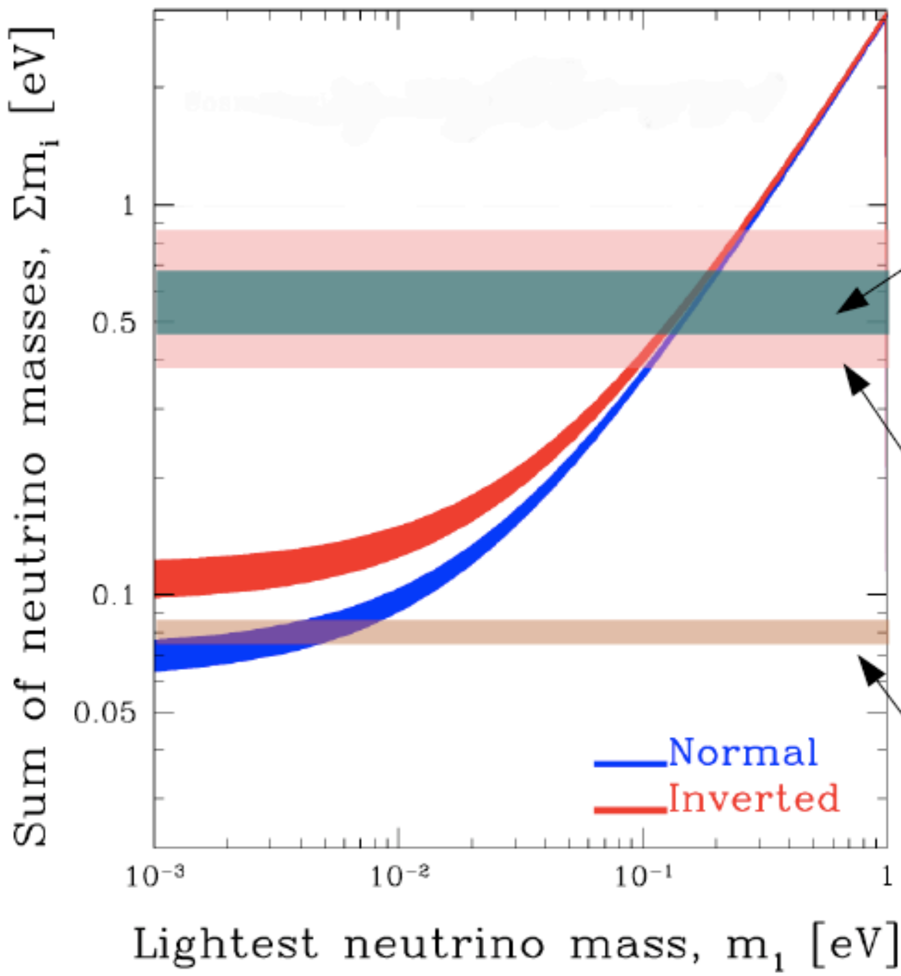
Planck sensitivity:

1. Planck only 0.26 eV
2. Planck + SDSS 0.2 eV
3. CMBR + grav. lensing 0.15 eV



From Planck "Bluebook"

Pre-Planck constraints and future sensitivities…



CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ HST+SNIa

$$\sum m_\nu < 0.44 \to 0.76\,\mathrm{eV} \quad (95\,\%\,\mathrm{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y[3]W 2010
Gonzalez-Garcia et al. 2010, etc.

Planck alone (1 year)

$$\sum m_\nu < 0.38 \to 0.84\,\mathrm{eV} \quad (95\,\%\,\mathrm{CI})$$

Perotto et al. 2006

Planck+Weak lensing (LSST)

$$\sum m_\nu < 0.074 \to 0.086\,\mathrm{eV} \quad (95\,\%\,\mathrm{CI})$$

Hannestad, Tu & Y[3]W 2006

Y.Y.Y. Wong (2012)

First Planck analysis (March 2013)

Planck XVI

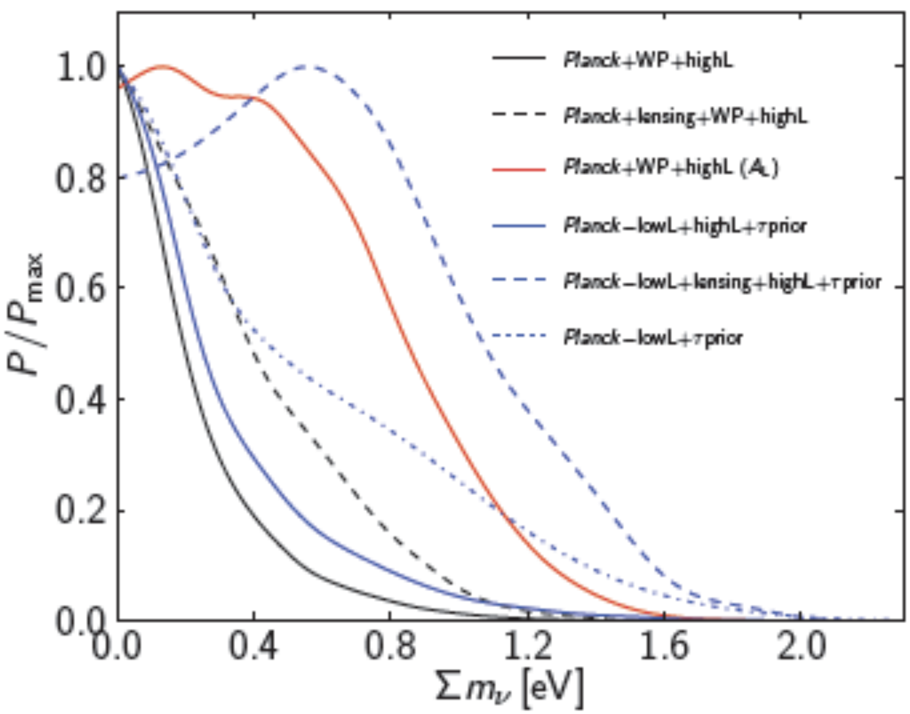
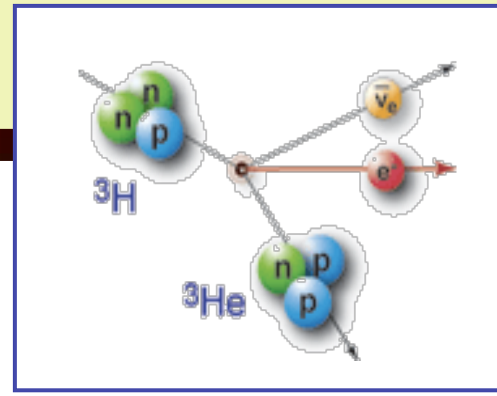


Fig. 26. Marginalized posterior distributions for $\sum m_\nu$ in flat models from CMB data. We show results for *Planck*+WP+highL without (solid black) and with (red) marginalization over A_L, showing how the posterior is significantly broadened by removing the lensing information from the temperature anisotropy power spectrum. The effect of replacing the low-ℓ temperature and (*WMAP*) polarization data with a τ prior is shown in solid blue (*Planck*−lowL+highL+τprior) and of further removing the high-ℓ data in dot-dashed blue (*Planck*−lowL+τprior). We also show the result of including the lensing likelihood with *Planck*+WP+highL (dashed black) and *Planck*−lowL+highL+τprior (dashed blue).

WP = WMAP Polarization data
A_L = weak lensing parameter
τ = optical depth at recombination

"…Planck lensing likelihood favours
larger Σm than the temperature power spectrum."

Neutrino mass from Beta Spectra



With flavor mixing:

$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\text{nuc}}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T) \sum_i |U_{ei}|^2 \left[(T_0-T)^2 - m_i^2\right]^{1/2}$$

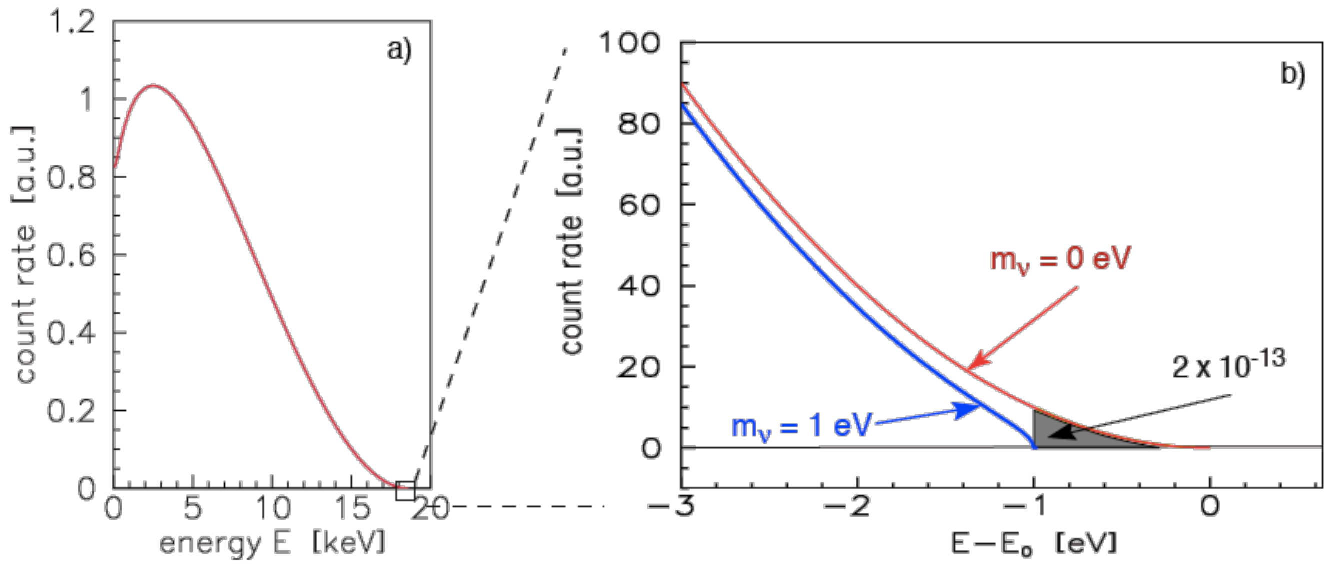
$$m_i^2 = \Delta m_{i0}^2 + m_0^2$$

mixing

neutrino masses

from oscillations

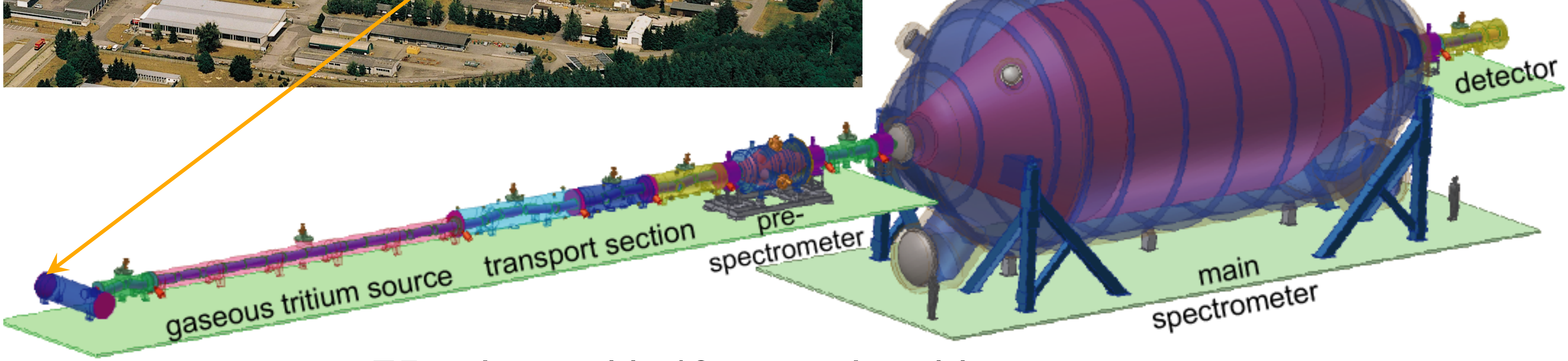
mass scale



KATRIN

At Karlsruhe Institute of Technology
unique facility for closed T_2 cycle:
Tritium Laboratory Karlsruhe

5 countries
13 institutions
100 scientists



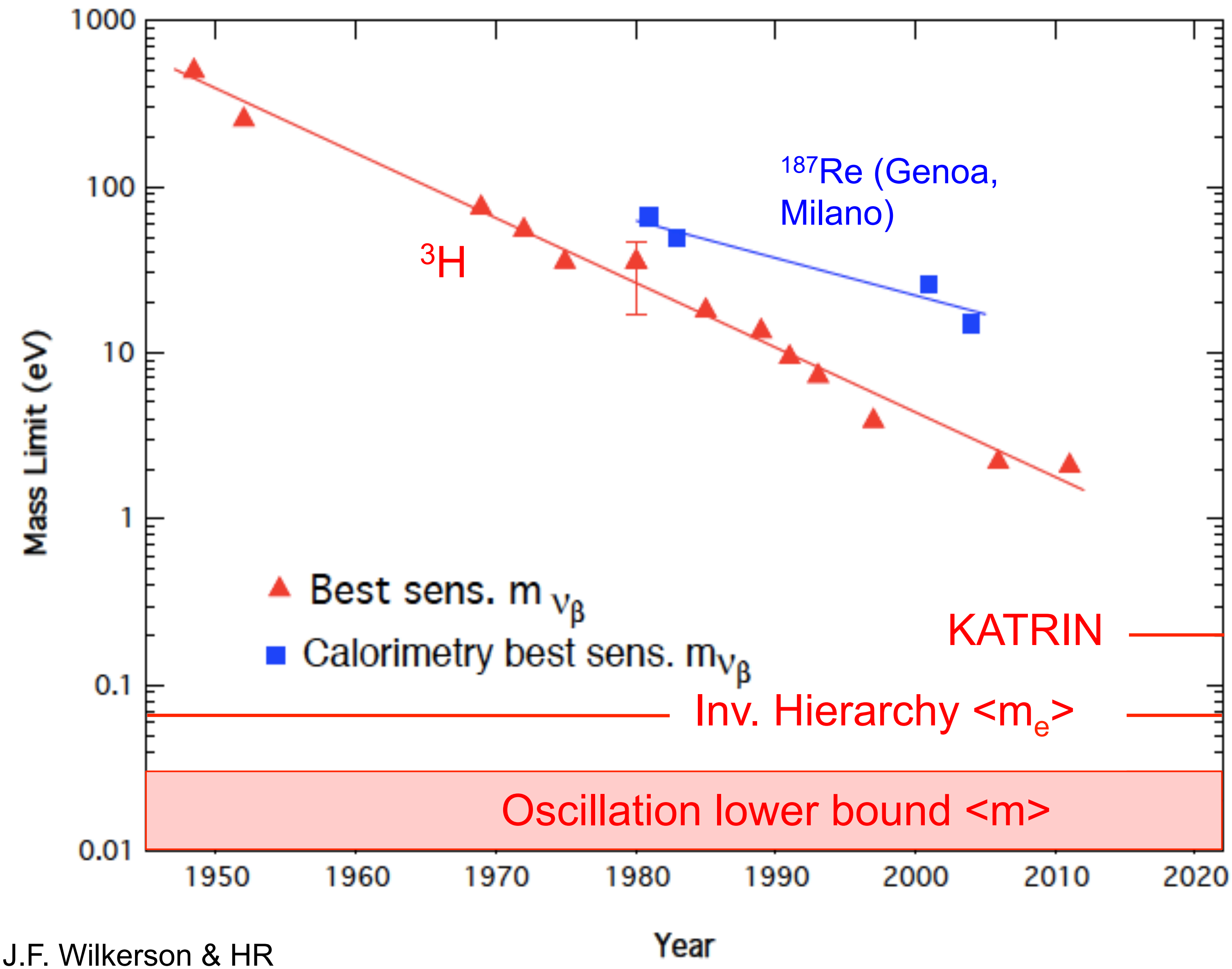
~ 75 m long with 40 s.c. solenoids


Dublin
IRELAND
Irish Sea
Leeds
Manchester
Liverpool
KINGDOM
Birmingham
Cardiff
London
Celtic Sea
Amsterdam
NETH.
Rotterdam
Bremen
Hamburg
Berlin
Bornholm
Gdansk
RUSSIA
BELARUS
Hrodna
Homyel'
Brest
Warsaw
Poznań
Oder
POLAND
Łódź
Wroclaw
Leipzig
Elbe
Essen
Cologne
Bonn
GERMANY
Brussels
Lille
BEL.
Guernsey (U.K.)
Jersey (U.K.)
Frankfurt am Main
Luxembourg
LUX.
Paris
Seine
Stuttgart
Munich
Strasbourg
Rhine
Prague
CZECH REPUBLIC
Brno
Kraków
Vistula
SLOVAKIA
CARPATHIAN MTS.
Bratislava
Danube
Vienna
Budapest
AUSTRIA
HUNGARY
Kiev
Rivne
Dnipro
UKRAINE
L'viv
Chernivtsi
Mykolayiv
Chisinau
Iasi
MOLDOVA
Odesa
Cluj-Napoca
ROMANIA
Bucharest
Constanța
Black Sea
Varna
Nantes
Loire
Bay of Biscay
FRANCE
MASSIF CENTRAL
Lyon
Bordeaux
Zürich
Bern
Vaduz
LIECH.
SWITZ.
Geneva
ALPS
Milan
Venice
Turin
Po
Ljubljana
SLOVENIA
Zagreb
CROATIA
BOSNIA AND HERZEGOVINA
Sarajevo
DINARIC ALPS
Belgrade
Serbia
BULGARIA
Sofia
Montenegro
Podgorica
Skopje
F.Y.R.O.M.
Tirana
ALB.
Istanbul
Bursa
TURKEY
Izmir
Thessaloniki
GREECE
Athens
Aegean Sea
Rhodes
Crete
Bilbao
Toulouse
MONACO
Genoa
SAN MARINO
Florence
Ligurian Sea
Adriatic Sea
Andorra la Vella
PYRENEES
ANDORRA
Marseille
Corsica
ITALY
APENNINES
Rome
VATICAN CITY
Naples
Porto
Zaragoza
Barcelona
PORTUGAL
Madrid
Lisbon
Tagus
SPAIN
Valencia
Balearic Sea
BALEARIC ISLANDS
Sardinia
Tyrrhenian Sea
Cagliari
Ionian Sea
Sevilla
Gibraltar (U.K.)
Málaga
Mediterranean Sea
Palermo
Sicily
Strait of Gibraltar
Ceuta (SPAIN)
Alborán Sea
Melilla (SPAIN)
Oran
Algiers
Tunis
Valletta
MALTA
Rabat
Casablanca
MOROCCO
ALGERIA
TUNISIA
Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
0
300 Kilometers
0
300 Miles
40
20
0

Neutrino Mass by NOT detecting neutrinos

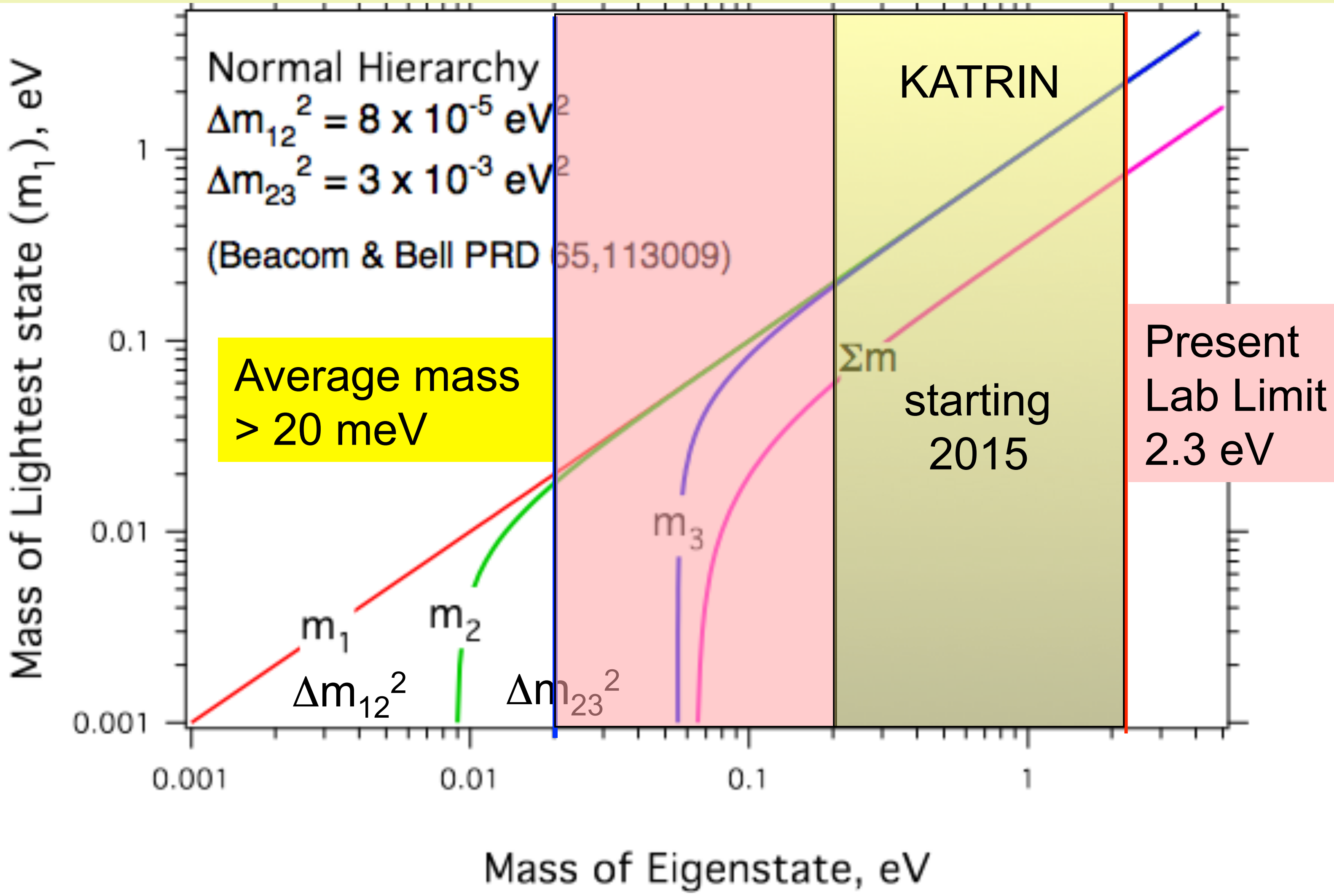
Arrival in Leopoldshafen: Nov 24, 2006

Neutrino Mass Limits from β decay



J.F. Wilkerson & HR

Mass Range Accessible



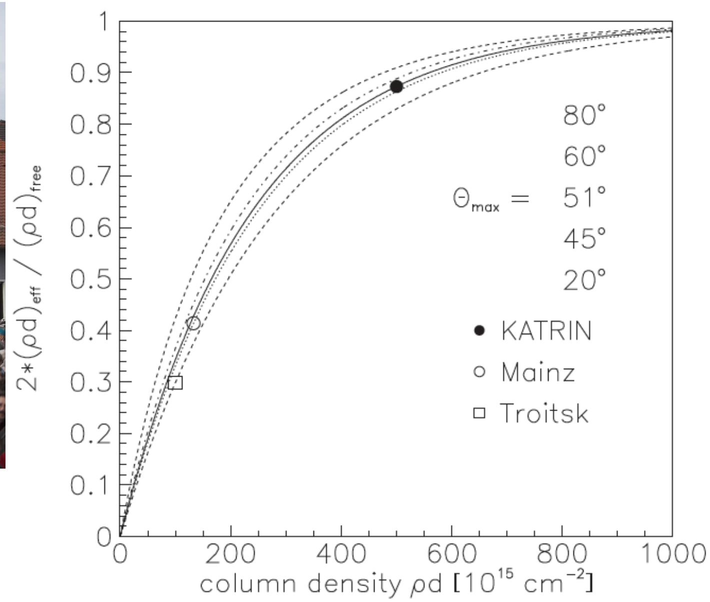
The Last Order of Magnitude

If the mass is below 0.2 eV, how can we measure it?
KATRIN may be the largest such experiment possible.

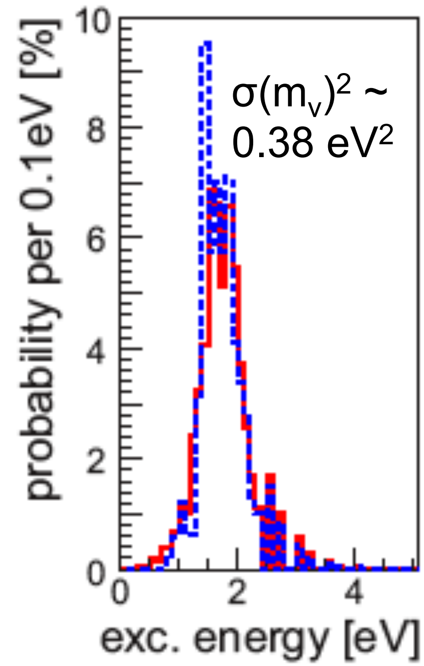
Size of experiment now:
Diameter 10 m.

$$\sigma(m_\nu^2) = k\frac{b^{1/6}}{r^{2/3}t^{1/2}},$$

Next diameter: 300 m!



Source T_2 column density near max



Rovibrational states of THe^+, HHe^+ molecule

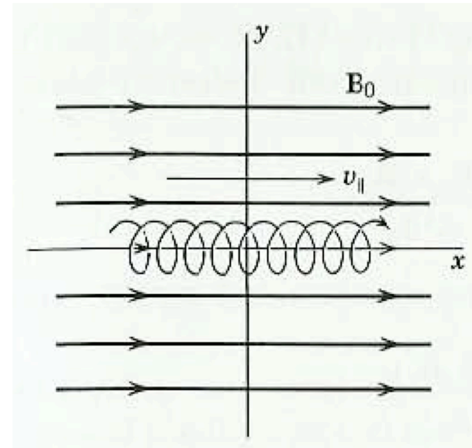
PROJECT 8

Cyclotron radiation from tritium beta decay

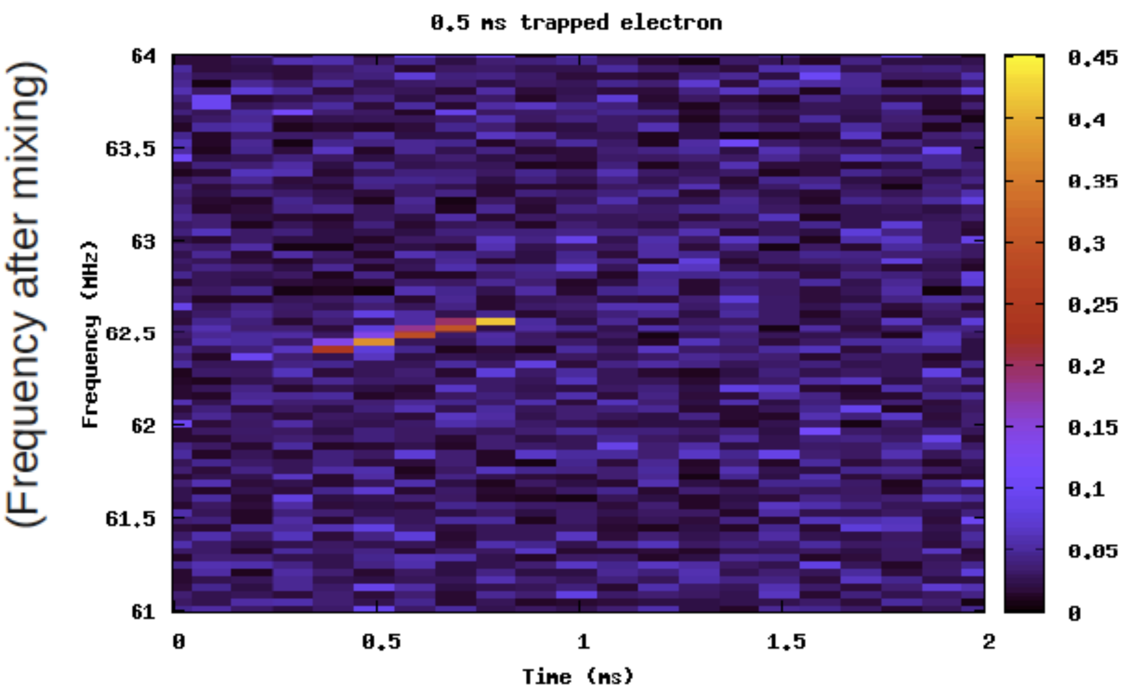
(B. Monreal and J. Formaggio, PRD 80:051301, 2009)

$$\omega = \frac{qB}{\gamma m} \equiv \frac{\omega_c}{\gamma}$$

$$\omega_c = 1.758820150(44) \times 10^{11} \text{ rad/s/T}$$



Radiated power ~ 1 fW



simulation M. Leber

Parameter	Value	Unit
Electron energy	18.6	keV
β	0.2627	
γ	1.0364	
Field	1	T
ω_c	27.009	GHz

Major objectives in Neutrino Physics

Known Unknowns

- ~~θ_{13}~~
- Hierarchy
- Mass
- CP violation
- Majorana or Dirac

Unknown Unknowns

- ~~OPERA~~
- $N_\nu \sim 4$ from cosmology
- LSND, MiniBooNE
- Reactor anomaly
- Ga source anomaly

(DOE Nuclear Physics plays a strong role)